PAST, CURRENT, AND FUTURE FOREST HARVEST AND REGENERATION MANAGEMENT IN INTERIOR ALASKA BOREAL FOREST: ADAPTATION UNDER RAPID CLIMATE CHANGE

By

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Abstract

The Alaska boreal forest is largely ecologically intact and provides various services, but is experiencing rapid, mainly climate-driven changes, and thus adaptation is essential. Systematic forest harvest management has occurred in central Interior Alaska for about 40 years, and this period is used in this study to examine the essential elements of adaptive management: monitoring, evaluating, and adjusting. In chapter 1, I examine historical relationships between forest growth and removals in the study area. My result shows that forest harvest management has relied heavily on natural regeneration. The harvest level was much lower than the overall annual allowable cut (AAC) level in the last 40 years. However, harvest activities were concentrated in road-accessible areas and white spruce stands. In chapter 2, I evaluate whether state forest harvest units are adequately regenerated after a period of 10 to 40 years under the typical low-input management. The results indicate that post-harvest regeneration has been largely successful based on the state regeneration standard established under the Forest Practices Act and follows a similar successional pattern to that seen following fire. In chapter 3, I examine whether harvest type, site preparation method, and reforestation technique resulted in differences in forest regeneration. The results indicate that clearcutting and/or site preparation increased tree regeneration, basal area, and biomass when compared to partial harvest and/or no site preparation. Planting of white spruce may only be necessary in specific circumstances, such as years with no/low white spruce seed crop, landscapes depleted of seed trees, or when early spruce dominance of the site is desired. In chapter 4, I identify the effects of landscape and forest management predictors on post-harvest regeneration in the study area and build post-harvest regeneration scenarios under different management practices and levels of climate change. The results show that post-harvest regeneration is largely influenced by site-level environmental

factors rather than management practices. Regeneration is projected to fail on many low elevation sites under the climate scenarios. As a result, forest management practices need to be adjusted specifically to the site and prepared for a climate regime shift. In chapter 5, I offer adaptive management approaches to prepare for the challenges of the future by synthesizing the knowledge and practices of the past, and the needs and challenges of today. Continued monitoring and evaluation is essential for adaptive management to be successful, particularly because of the short history of systematic forest harvest management in the study area. Some of the key forestry databases I analyzed need substantial improvement. However, this study provides the basis to build adaptive forest management for the first time in boreal Alaska, which requires adaptive approaches sooner than elsewhere due to rapid climate change now well underway.

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General Introduction

The boreal forest covers about 30% of forest land on the earth (Brandt *et al*., 2013) and provides various ecological services, such as habitat provision, water cleansing, and climate regulation by carbon sequestration (Bonan *et al.*, 1992; Pan *et al.*, 2011), and essential social and economic values for human lives, especially for indigenous people (Nelson *et al.*, 2008). Many boreal regions have experienced extensive forest harvesting, which caused deforestation, forest degradation, and forest fragmentation in many boreal regions (Ostlund *et al.*, 1997; Lofman and Kouki, 2001; Boucher *et al.*, 2014). Boreal forests in Canada and Fennoscandia have experienced large-scale short-rotation clearcutting primarily for wood production with only a marginal thought to other values and services (Esseen *et al.*, 1997; Ostlund *et al.*, 1997; Chapin *et al.*, 2004; Potapov *et al.*, 2008; Gauthier *et al.*, 2015). To maximize production, clearcutting was followed by planting of crop trees, which created homogenous species and age forest structures (Wittwer *et al.*, 1990; Esseen *et al.*, 1997; Ostlund *et al.*, 1997). Further development and extraction of wood from boreal forests is likely due to increasing population (Gauthier *et al.*, 2015), although boreal forest management has started to adopt a more ecological approach attempting to sustain multiple values of forest resources (Wittwer *et al.*, 1990; Esseen *et al.*, 1997; Spence, 2001; Bergeron, 2004). Compared to those areas, Interior Alaska boreal forest is relatively intact (Potapov *et al.*, 2008), providing a unique opportunity to identify largely natural ecological processes as a basis for adaptive management.

In Interior Alaska boreal forest, logging was active during the period of the gold rush and rapid urban development from the late 19th to the early 20th century (Wurtz *et al.*, 2006). However, logging in this time period has not been documented well (Roessler, 1997). Operational forest harvest management and documentation begun after statehood in 1959. A large area of the productive forest land of boreal Alaska is managed by the state, but other ownerships, including Native allotments, Native Corporation, Borough, University, and other private owners, exist in the region for a small portion. Since the late 1960s, the local demand for wood harvest has been relatively low in central Interior Alaska, and export markets, mainly to Asia, have only been profitable for limited periods of high prices (Wurtz *et al.*, 2006). However, a comprehensive empirical study of historical harvest activities, demand, or resource availability across ownerships in central Interior Alaska boreal forest, which is essential for a sustainable approach, has not been available previously.

More recently, demand for woody biomass is increasing due to increased interests in wood biomass energy in Interior Alaska (Fresco and Chapin, 2009). As of 2015, nine wood biomass energy facilities have been built, 10 are under construction, and more than 11 are in design or feasibility status in Interior Alaska (Alaska Energy Authority, 2015). As the new wood energy facilities begin to operate, demand for wood will increase in this region (Fresco and Chapin, 2009). The increased wood biomass energy demand will require expanded forest harvest and a change in product emphasis from large-dimension white spruce to additional species at smaller diameters. In addition, the harvest cycle will become shorter for biomass harvest than for large-dimension wood products, requiring more frequent regeneration (Janowiak and Webster, 2010). In order to meet the needs of this evolving forest management situation on the sustained yield basis, it is crucial to understand post-harvest regeneration of all the woody species that could meet the new biomass demand.

In Alaska, a mandate for sustainable yield was adapted within Article VIII of the State's Constitution. Elaboration of the sustainable yield mandate in the context of forestry was developed in the Alaska Forest Resources & Practices Act (FRPA)[1]. This was followed by the establishment of FRPA regulations[2]. According to these regulations, reforestation is required for all forest harvests in the State with stocking levels dependent on the exact location of the harvest. Additional regeneration efforts are required in Interior and South-central Alaska, when regeneration in the harvest area fails to meet State regeneration standards within seven years following harvest. The Alaska Division of Forestry (AKDOF) is required by the FRPA[3] to conduct regeneration surveys within seven years after harvest to ensure the stand is adequately regenerated. However, because forest regeneration in Interior Alaska may take place over an extended period of time following disturbance (Viereck and Schandelmeier, 1980), it is impractical to determine if natural regeneration has been successful based on short term surveys. Therefore, a comprehensive, long-term investigation of tree establishment and post-harvest growth is necessary to determine whether low-cost forest management with heavy reliance on natural regeneration has met at least the first requirement sustained yield, which is successful tree regeneration.

The boreal forest ecosystem is now going through profound changes due to human activities (Brandt *et al.*, 2013). Among those, climate change is the major challenge Alaska boreal forest is facing for the current and future management. The effects of climate change is more profound and rapid in the Alaska boreal region because of a greater amount of warming

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[1]AS 41.17

[2] Alaska Forest Resources and Practices Regulations (11 AAC 95) implement and interpret FRPA (AS 41.17). The requirement of regeneration survey is mentioned in section 385 of the regulations. Booklets of FRPA and the regulations are available at http://forestry.alaska.gov/forestpractices.

[3]FRPA 11 AAC 95.385

compared to forest regions in lower latitude (Hartmann *et al.*, 2013; Chapin *et al.*, 2014). Temperature increases have already begun affecting Interior Alaska boreal forest in many ways, including changing tree growth, moving tree lines, modifying wildfire behaviors, and warming or thawing permafrost (Barber *et al.*, 2004; Wilmking *et al.*, 2004; Johnstone *et al.*, 2010). An effective forest management is required to adapt to this rapid climate warming using knowledge from the past, understanding of the current condition, and a reliable prediction of the future.

Due to the heterogeneous nature of the data and the multivariate ecosystem topic, we use the TreeNet algorithm (boosted regression trees; Salford System Ltd), known to find and confirm patterns from such situations (Friedman *et al.*, 2000). The TreeNet is a specific and fine-tuned stochastic gradient boosting algorithm, which creates many weak learners with improvements using the residuals from the previous trees and creates a strong learner that is optimized (Friedman *et al*. 2000). Stochastic gradient boosting was improved from gradient boosting by drawing random subsets at each iteration. The TreeNet algorithm allows us to predict the post-harvest regeneration accurately with a limited amount of field observations in a multivariate fashion with a large number of predictors (Friedman *et al.*, 2000). The TreeNet algorithm also help us obtain a better understanding of complex processes of post-harvest regeneration because of its ability to apply a large and realistic number of ecosystem predictors that are affecting regeneration.

Systematic forest harvest and documentation has occurred for 40 years in central Interior Alaska. This is the first broad scale GIS-based study in central Interior Alaska to compile the empirical data of silvicultural forest harvest management and examine the effects of mature forest harvest on regeneration across time and space in an operational context. Forty years is not adequate to examine the entire rotation, which is essential for the complete adaptive management. However, this study provides the basic framework for successful implementation of adaptive forest management for the first time in boreal Alaska. While the subject of adaptation to climate change involves a vast amount of information in many different specialized fields, I believe it is useful to provide an initial synthesis of what existing information indicates for the key concerns of forest management where climate change is an overriding issue.

In chapter 1, I compile and analyze the history of commercial harvest in central Interior Alaska boreal forest over the last 40 years for sustainable forest harvest practices. Reviewing historical harvest activities provides for the identification of important trends and possible adaptations for the future harvest and regeneration management. In chapter 2, I evaluate success of post-harvest regeneration up to 40 years in terms of stem density and biomass accumulation. To achieve this objective, I evaluate whether harvest units are adequately regenerated up to 40 years following a timber harvest based on the current state yield standards set forth in FRPA. This study also examines low-input management in a matrix of vast natural forest, which is the characteristic of boreal forest management in central Interior Alaska. In chapter 3, I evaluate harvest methods and the subsequent management practices on post-harvest regeneration. To achieve this objective, I evaluate whether any of the management practices (harvest type, site preparation method, and reforestation method) resulted in differences in regeneration. In chapter 4, I identify how and to what degree landscape and forest management predictive factors influence post-harvest regeneration and build scenarios of plausible future forest conditions under different levels of future climate warming and management practices in central Interior Alaska. In chapter 5, I offer a framework and options for adaptive forest harvest management through an assessment of data from the Alaska boreal forest, a region experiencing the most rapid climate change globally. To achieve this goal, I compile and evaluate for the first time available silviculturally practiced management data (roads, timber harvest, wildland fire) over the past 40 years, along with our sampling of tree regeneration in harvest units. The objective is to offer an overview assessment of forest harvest management including (1) indicators of sustainable timber yield and management practices, (2) characteristics of forest harvest management compared to wildfire, and (3) potential options relating to forest harvest and regeneration management approaches in light of climate change.

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Chapter 1. Perspectives on Sustainable Forest Management in Interior Alaska Boreal Forest: Recent History and Challenges[1]

1.1. Abstract

The boreal forest of Alaska offers a unique opportunity to examine forest sustainability issues, because sustained yield forest management has been practiced for only 40 years and is still small in scale. This study examines historical relationships between forest growth and removals in central boreal Alaska over the last 40 years in order to contribute to the development of sustainable forest harvest practices. We conducted analyses using forest inventory, annual allowable cut (AAC), and forest harvest and reforestation databases. We found that forest harvest level in the last 40 years was much lower than the available calculated AAC level, but harvest activities were concentrated in road accessible areas and white spruce (*Picea glauca* (Moench) Voss) stands older than rotation. An expansion of the road network, or a shift in harvest and utilization from white spruce to hardwood would contribute to sustainable wood yield. Regenerating forest stand types and ages equivalent to those harvested would require a reduction of AAC, or an adjustment of AAC by zones according to accessibility. Continued and improved monitoring will be required to provide the necessary information for sustainability issues in boreal Alaska, particularly in the developing stands harvested over the past 40 years.

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[1] Miho Morimoto and Glenn P. Juday, Perspectives on sustainable forest management in Interior Alaska boreal forest: recent history and challenges. Prepared for submission in New Forests.

1.2. Introduction

The boreal forest represents about 30% of the forest land on the earth (Brandt et al. 2013) and provides various ecological services, such as wood production, habitat provision, water cleansing, and climate regulation by carbon sequestration (Pan et al. 2011). In Interior Alaska, boreal forest is an essential vegetation type especially to indigenous people relying on wildlife and wild vegetation as their food source (Nelson et al. 2008). Wood products from the boreal forest supported the gold rush and development of the urban areas (Wurtz et al. 2006). However, the global boreal forest has experienced rapid climate and other changes which threaten the various ecological services the boreal forest provides (Brandt et al. 2013; Gauthier et al. 2015). Historically the primary focus of forest management was a maximum production of wood products, often with only implicit regard for forest ecological services in many boreal regions (Ostlund et al. 1997). A large portion of boreal Canada, Fennoscandia, and Russia has experienced loss of species diversity through large-scale clearcutting with planting of crop trees for maximum wood production (Ostlund et al. 1997; Wittwer et al. 1990). However, a new appreciation also has emerged on the values of forest ecological services other than wood products. Under such circumstances, sustainable forest management which aims to sustain multiple values of a forest, including both wood production and ecological services, is becoming a more important approach (Forest Europe et al. 2011; Kohm and Franklin 1997).

A basic requirement of sustainable forest management is an assessment of the relationship between forest growth and tree removals. More generally, sustainable forest management needs to be adjusted based on multiple factors, such as global and local demand, primary productivity required for ecosystem services, and resource availability. Demand for wood is increasing for biomass energy generation (Fresco and Chapin 2009a), which will expand harvest activity in Interior Alaska. In order to conduct forest harvest in a sustainable way, it is desirable to identify historical relationship between forest growth and removals across ownerships in Interior Alaska boreal forest as a basis for future adaptations. However, in Interior Alaska, a comprehensive empirical investigation of historical harvest activities had not been conducted, and the relationship between harvest and resource availability had not been examined before this study.

In central Interior Alaska, systematic forest harvest management and record keeping began in the late 1960s to 1970s on state forest land (Alaska Division of Forestry 2013a) and private lands (Tanana Chiefs Conference 2015), mainly Alaska Native Corporation established under the Alaska National Interest Lands Conservation Act (Hull and Leask 2000). Unconstrained logging occurred in the early 1900s near a few early populations centers and gold mines (Wurtz et al. 2006). These early tree cutting activities took place in the landscape of the study area, but likely overlapped the land base currently dedicated to sustained yield timber management only to a limited extent. Some areas of early logging are documented (Roessler 1997), but information on the total extent is not currently available. As a result, in this study we only analyze systematic forest harvest management that occurred in central Interior Alaska since the late 1960s. Reviewing past harvest activities allows the identification of important trends and possible adaptations for future harvest and regeneration management. The goal of this study is to compile and analyze the history of commercial harvest in central Interior Alaska boreal forest, an area of 250,000 km^2, over the last 40 years in order to contribute to developing sustainable forest harvest and regeneration practices.

1.3. Interior Alaska Boreal Forest and Forest Management Agencies in the Region

Interior Alaska boreal region stretches from the Alaska Range in the south to the Brooks Range in the north, and Canadian border in the east to the Chukchi Sea in the west, covering about 47 million ha (Figure 1.1a). The climate of the central Interior study area is strongly continental, with extreme winter temperatures as low as -50°C, resulting in low plant species diversity with three coniferous and three broadleaf species. The primary tree species are white spruce, black spruce (*Picea mariana* (Mill.)), Alaska birch (*Betula neoalaskana*), and quaking aspen (*Populus tremuloides* Michx.), and the minor species are balsam poplar (*Populus balsamifera*), and tamarack (*Larix laricina*) (Labau and van Hees 1990). Even though several willow species are important for browse, especially for moose, willows accounts for only a small amount of the woody stems in harvested stands (4.6% in density and 1.1% in basal area, this thesis) and willow harvest is currently not commercially viable.

The principal long-term NWS First Order station for the study area is Fairbanks International Airport (1948-present; 133 m). The Fairbanks Airport climate record is a single point record taken on a grass surface near the runway (not forest). Due to the general lack of climate measurements in Alaska, the Fairbanks Airport climate record is traditionally used as one reference point in a number of analyses of climate trends and forest growth studies (Juday and Alix 2012; McGuire et al. 2010; Wilmking et al. 2004). Mean annual temperature at Fairbanks Airport is -2 °C and annual precipitation of 270 mm, with extreme temperatures ranging from -50 °C to 35 °C. The period between freezing temperatures in the early 21st century is approximately 123 days at Fairbanks, an increase from 85 days in the early 20th century (Wendler and Shulski 2009). However, climate in the region varies substantially according to factors such as elevation and aspect (Shulski and Wendler 2007). Continuous, locally relevant climate data have been generated by downscaled climate data for the study area (SNAP 2015). The combination of precipitation and temperature across much of lowland central Alaska is near the moisture/precipitation limit for the survival several of the boreal tree species (Juday et al. 2015; Thompson et al. 1999).

In summer in Interior Alaska, warm and dry weather creates the conditions for wildfires, triggered primarily by lightening. The boreal forest is a stand-replacement disturbance driven system (Chapin et al. 2006; Foote 1983; Rowe and Scotter 1973), of which fire is the major disturbance (Murphy et al. 2000). Wildfire plays essential roles of reducing organic soil depth, increasing element availability, initiating succession, and increasing biodiversity of the boreal forest (Chapin et al. 2006).

In the Interior Alaska boreal region, a large area of productive forest is managed by the Alaska Department of Natural Resources, Division of Forestry (AKDOF) within the Tanana Valley, which is drained by the large silt-bearing Tanana River (Hanson 2013). The Tanana Valley State Forest (TVSF) and other state “forest classified” lands are termed “state forest lands” in this study. State forest lands in the Tanana Basin cover 1.16 million hectares, or 2.5% of the total land area of Interior Alaska (Table 1.1, Figure 1.1a), of which ~75% is forested. State forest lands are grouped into four management areas: Fairbanks, Kantishna, Delta, and Tok (Figure 1.1b-e). Other major ownerships of productive forest land within the Tanana Valley, termed “other forest lands,” included in this analysis are the Fairbanks North Star Borough, individual Native allotments, and Toghotthele Native Corporation (Table 1.1, Figure 1.1b-e). There are other ownerships of productive forest lands within the study area, including University of Alaska, Mental Health Trust land (http://mhtrustland.org), as well as other Native

Corporations, which together make a relatively small contribution to the historical harvest. These other lands were not analyzed in this study.

1.4. Methods

We summarized available forest inventory data, obtained from state forest lands and Toghotthele Native Corporation lands. AKDOF created a land cover map which incorporated the inventory data based on field measurement and aerial photo interpretation (Hanson 2013). Inventories of Toghotthele Native Corporation lands are not spatial data, but compile area and volume of the major vegetation types (Tanana Chiefs Conference 2007). Forest inventory analysis or data were not used for Native Allotments (small, individually owned parcels) and Fairbanks North Star Borough lands because of minor timber harvest activity or unavailable data.

We analyzed forest harvest and management practices on state and other forest lands in terms of harvest volume and area, and types of management practices that were used from 1969 to 2012. We obtained timber harvest and reforestation management databases from AKDOF Fairbanks and Tok area offices (Alaska Division of Forestry 2013a). The Fairbanks area office manages Fairbanks, Kantishna, and Delta management areas. For other forest lands, we obtained the timber harvest and reforestation databases from Tanana Chiefs Conference (TCC). All the databases are GIS-based records of the location and type of management activities that have occurred on the management areas.

The databases contain records of timber harvest and reforestation, such as geographical location, type and date of harvest, site preparation, and reforestation, contractor and harvest area (Appendix 1.1-1.8; Alaska Division of Forestry 2013, Tanana Chiefs Conference, 2015). The completeness of the timber sale and reforestation databases varies among the management offices. Fairbanks and Kantishna management areas cover the largest area and have more complete database than any others, but none of the databases are complete in all fields, nor free of apparent errors. Thus, we made corrections to the databases to increase accuracies of analyses, and simplified methods of management practices as described following.

Inconsistencies and incomplete records of date of harvest were a particular problem. The recorded date of harvest may only be the transaction date, and actual timber cutting may have occurred over a number of years. We identified year of harvest using either year/date of harvest, expiration or terminated date of timber sale, timber sale files, and/or aerial photography from 2006 and 2012, depending on the data availability. For Fairbanks and Kantishna management areas, we identified year of harvest using date of harvest or terminated date of timber sale, and improved the accuracy of previous records by checking timber sale files and aerial photography. Timber sale files contain timber sale inspections, which are aimed to record logging progress. Some units have detailed and frequent inspections but others have limited and incomplete inspections. When date of harvest was missing in the database (524 out of 853 harvest units), we attempted to find date of harvest completion from the inspection records.

Large timber sales often contain multiple harvest units which might have been harvested in different years, yet date of harvest was recorded as the same date for all the units within the sale. We checked the timber sale inspections of the large timber sales, and updated year of harvest for each harvest unit where possible. When we could not find the records, we used terminated date of timber sale for year of harvest. For the recent timber sales (2006 and later) that have no termination date, we checked aerial photography from 2006 and 2012 to see if the timber sale was harvested anytime between this time period. If the sale was not logged in this time period, we concluded that the sale had not been logged as of 2012. In Delta and Tok management areas, date or year of harvest, and date of termination were not recorded, so we used date of expiration for year of harvest. For Toghotthele Native Corporation, Native allotments, and FNSB lands, we used the recoded date of harvest. Even after the data adjustments and additions, year of harvest is missing for several harvests, especially in Tok (103 missing out of 137 recorded).

Timber volumes that will be harvested are estimated before harvest for sawlog and fuelwood from the entire timber sale, but actual harvested volumes are not recorded. We used the pre-sale estimated timber volumes as harvested volume, although the timber volume and the actual harvested volume can be different. In the Fairbanks and Kantishna management areas, timber volume records are the total volume to be harvested for sawlog and fuelwood from the entire timber sale even when the sale contains multiple units. As a result, we estimated harvested volume at the timber sale unit level. In timber sales that contain multiple units, we attempted to distribute harvest volume to each unit for sawlog and fuelwood of each species. For spruce sawlog, we used harvest volume of sawlog per acre (SAW_CCF_AC, see Appendix 1.1), and multiplied it by area (acre) of harvest. For fuelwood, we first used harvest volume of fuelwood per acre (FUEL_CCF_A, see Appendix 1.1), and multiplied it by area of harvest to obtain the total volume of fuelwood harvested in each unit. Then we calculated the proportion of fuelwood harvest volume by species using records of birch, spruce, and aspen fuelwood volume (BIRCH_VOL, SP_FUEL_VO, and ASPEN_VOL, see Appendix 1.1) for the timber sale. Finally, we multiplied the harvest volume of fuelwood for each harvest unit by the proportion of fuelwood harvest volume by species in the sale to reconstruct fuelwood volume by species for each harvest unit.

Harvest type, site preparation technique, and reforestation methods were simplified for a more meaningful interpretation (Table 1.2). Harvest type was categorized into seven categories (Table 1.2). Site preparation technique was simplified into no site preparation versus scarification, combining all types of scarification into a single category (Appendix 1.2, 1.5, 1.6, and 1.8). Reforestation methods were classified into (a) natural regeneration, (b) planting of seedlings, and (c) direct seeding, regardless of species, timing, or number of times or density planted (Appendix 1.2, 1.5, 1.6, and 1.8).

Although the various databases contain geographical information, some polygons do not match the actual harvest boundary, especially in old timber sales. In the 1970s, some large timber sales were laid out across a large forest area and harvest was allowed anywhere within the boundary (Doug Hanson, personal communication). This resulted in some mapped harvest units in the database that were larger than the actual area harvested.

In order to identify whether harvested timber was used locally or exported, we examined white spruce sawlog harvested volume by purchasers. We categorized purchasers from Interior Alaska or not (others). It is important to note that we cannot conclude whether harvested timber was locally used or not just by purchasers because local loggers might have exported products (Paul Keech, personal communication). Nonetheless, this categorization reflects an important trend in harvest activities in the study area.

We used annual allowable cut (AAC) as calculated by AKDOF (Hanson 2013) and Toghotthele Native Corporation to analyze sustainable wood yield on state forest lands and Native Corporation land. The AAC is based on site index, rotation age, and volume estimates of the major forest land cover types (Hanson 2013). First, annual allowable harvest area was calculated for each major forest cover type by dividing the total area of a given forest cover type by projected rotation age of the forest cover type. Rotation age was established based on the median site index and the inferred age representing culmination of mean annual increment (Farr 1967). A spruce rotation age of 120 was used regardless of varying site index. The calculated AAC is conservative because it uses the highest rotation age in the range. The AAC volume was then calculated by multiplying the annual harvest area by the average volume per area for each forest cover type. The AAC volume was reduced by 5% and 1% for white spruce and hardwood stands, respectively, to compensate for any unknown factors following the management plan (Alaska Department of Natural Resources 2001; Hanson 2013). Research natural area and experimental forest designations are also excluded from AAC calculation (10,431 ha). It is important to note that the accuracy and reliability of the AAC depends largely on the growth data, which was obtained from a study in 1967 (Farr 1967) for this AAC calculation. As a result, more recent, updated growth data is desirable for AAC calculation. However, the calculated AAC is still useful to evaluate harvest level in the study area, especially because of the conservative calculation.

Access is a major constraint on forest management in Interior Alaska (Wurtz et al. 2006). We identified the area and number of harvested units that fall within zones of 1 km intervals up to 4 km from the nearest road feature. The AKDOF data layer for road features includes highways, primary all-season or winter roads, secondary all-season or winter roads, and spur roads (Doug Hanson, personal communication). Primary roads are long-term persistent with moderate to heavy use, secondary roads are medium to long-term persistent with light to moderate use, and spur roads are for the short-term with light use (Alaska Department of Natural Resources 2001). We included all roads existing as of 2013 in the AKDOF road data layer (Alaska Division of Forestry 2013b), and as a result, some of the roads might not have existed at the time of harvest. However, forest roads are generally built when access to harvest is required so we believe that the error in the distance to road parameter is marginal. We also calculated the proportion of state forest lands that is “mature white spruce” or “birch dominant” stands within 1, 2, 3, and 4 km of road features to analyze timber accessibility. In this analysis, we classified mixed sawlog stands of any type containing white spruce as mature white spruce stand. In the study area, a large majority of sawlog size trees in mixed spruce-hardwood stands is likely white spruce. Our birch dominant stands include birch, birch-aspen, and birch-black spruce types including both sawlog and pole sizes. We included pole size in birch dominant stands because birch is less likely to reach the sawlog size at maturity compared to white spruce. Birch pole timber can be used for short-rotation (as short as 70 years) wood biomass harvest. The analysis we report here was conducted only for state forest lands because other ownerships do not have a complete database.

1.5. Results and Discussion

1.5.1. Forest Composition

On state forest lands, the greatest area of forest cover is black and white spruce/hardwood forest, and white spruce/hardwood forest (Figure 1.2a). Extensive areas of mixed black spruce forest occur on cold soils underlain by permafrost (e.g. Aquic Cryorthent, Histic Pergelic Cryaquept). Permafrost dominated sites, because of their low forest productivity, are generally not harvested (Bonan 2016; Van Cleve and Yarie 1986). However, wood biomass harvest, now expanding in the Alaska boreal region, could potentially utilize small black spruce material, and harvest of this type may expand in the future. In contrast, white spruce is the most productive stand type in central Interior Alaska, except for balsam poplar which covers a small area in floodplains (Viereck et al. 1983), and pure white spruce stands sustain the greatest biomass on state forest lands (Figure 1.2b). Wood demand was much greater for white spruce than hardwood species, mainly birch and aspen over the last half-century (Wurtz et al. 2006). As a result, during the period of analysis most timber harvest occurred in white spruce stands.

On Toghotthele Native Corporation lands, pure or mixed white spruce forest cover the greatest area (Figure 1.3a), but hardwood forest also covers about one fourth of the land (Figure 1.3a). Wood volume on this ownership is mostly composed of pure white spruce, mixed white spruce and hardwood, and hardwood types (Figure 1.3b, c).

1.5.2. Historical Area and Volume of Harvest

Harvested area and volume to date in Interior Alaska boreal forest since late 1960s are small, compared to the vast total area and large aggregate volume of the forest (Table 1.3). The total area harvested on state forest lands from the start of record collection in 1972 to 2012 is about 10,973 ha out of 871,263 ha of total timberland on state forest lands (Table 1.3) or 1.8%. Harvest activity on state forest lands was continuous from the early 1970's, with great variability among years (Figure 1.4a). On other forest lands, harvest activity occurred sporadically, with a few peaks over the last few decades (Figure 1.4b).

This initial compilation of harvest volume, which we report here, needs to be interpreted with caution. State forest lands, in general, have more detailed records of harvest volume than other forest. State forest management areas, except for Tok, have maintained a record of harvest volume by species and products (sawlog vs. fuelwood), but other forest lands have not. In addition, the volume results are not comparable between state and other forest lands because the units used for volume are different (cubic foot for state versus board foot for other forest lands) and they are not consistently convertible. Finally, harvested volume records are missing for many units in the Delta and Tok management areas, and on Toghotthele Native Corporation lands (Table 1.4). Overall, we were able to compile harvested volume records for about 70% of the total area harvested (Table 1.4), indicating that harvest volume figures compiled for this study are an underestimate. It is important to note that the Tok management area has overall lower standing volumes per area than the Fairbanks, Kantishna, Delta, and Toghotthele (48 $m^3 \cdot ha^{-1}$ versus 68-79 $m^3 \cdot ha^{-1}$, respectively). As a result, the harvest volume missing from available records cannot be directly extrapolated from a simple expansion of the average state forest harvest volume per hectare. We did not estimate missing harvest volume data because the lack of information on harvest type and harvested volume by species would introduce high variability in the estimate.

On state forest lands, annual area and volume harvested was quite low from 1972 until early 1980s except for 1972 and 1974 (Figures 1.4a and 1.5a). The large area of harvest in 1972 and 1974 probably represents an overestimate because of partial harvest in large sales (Doug Hanson, personal communication). In the mid-1980s, harvest area and volume gradually increased until the early 2000s in response to salvage and sanitation harvest following a large fire in 1983 (Juday 1985) and increased demand for spruce sawlogs in the Asian market in the 1990s (Brackley et al. 2009; Wurtz et al. 2006). Harvest area and volume decreased after early 2000s due to the downturn of wood product demand in the Asian market (Wurtz et al. 2006).

Spruce sawlog was purchased mostly by local loggers except for the 1990s on state and other forest lands and for the late 1960s on other forest land (Figure 1.6). Although local loggers might have exported products and non-local purchasers might not have exported products internationally, it is apparent that the increased demand from non-local purchasers reflects a period of increased export of white spruce sawlog to the Asian market, particularly Japanese market (Brackley et al. 2009).

During the period of analysis, harvest activities on other forest lands was lower than state forest (Table 1.3). The greatest area of harvest occurred on Toghotthele Native Corporation lands (Table 1.3, Figure 1.4b). Harvested area on other forest lands peaked at 1969, 1976, and 1979 (Figure 1.4b) but harvest volumes are not recorded for 1976 and 1979 (Figure 1.5b).

1.5.3. Perspectives on Sustainability from Annual Allowable Cut (AAC)

Sustainability can be considered from many different perspectives, such as wildlife habitat, soils, climate regulation, and social values, and so the amount of wood removal alone cannot depict the whole picture of sustainability (FAO 2015; IEG 2013). However, in terms of sustaining wood production two principal options are, 1) replacing stand types and structures of the harvested stands with equivalent stands in the regenerated forest, and 2) sustaining wood volume production of any species over time. The first perspective emphasizes environmental values (sustaining historic age structures, especially mature and old-growth forest) and the second is based on wood product potentials (often based on the shortest possible rotation). In managed landscape, mature white spruce can become the most limiting habitat for some wildlife species (Euler 2005; Haggstrom and Kelleyhouse 1996), particularly because mature white spruce is the preferred forest type for harvest. However, forest management regulation in the study region for wildlife habitat protection is limited. White spruce in particular is also vulnerable to increased loss from fire and insects due to temperature increases (Allen et al. 2015; Usher et al. 2005). Those environmental values and vulnerabilities provide a rationale for evaluating sustainability from the equivalent stand replacement perspective. Using the average

age of the forest types in the AKDOF inventory (Hanson 2013), in order to replace the harvested old-growth white spruce stands of our study area with stands of equivalent age (120-175 years average age) instead of stands harvested at a projected 120 year rotation, the harvest level would need to be about 25% lower than the AAC level. In addition, the potential for harvested stands that have mostly regenerated into broadleaf dominated young stands to eventually become white spruce dominated is not known.

A comparison of harvest activity to annual allowable cut provides a perspective on the relative degree or magnitude of historical utilization of wood volume. Throughout the period of our analysis, the total harvest volumes of white spruce and especially birch and aspen were much lower than the AAC on state forest lands (Table 1.5). Harvest volume of all white spruce, birch, and aspen were greatest in the Fairbanks area, but even there were only 23%, 3%, and 0.5% of AAC volume for these stand types, respectively. White spruce sawlog was the major harvested product category, accounting for about 90% of harvested volume on state forest lands (Figure 1.4a). A total of 1,266,026 m^3 white spruce sawlog was harvested from all state forest lands during the period 1972-2012, which is an average of 11% of allowable cut volume of total state forest lands. The overall mean of annual white spruce harvested volume is 32,218 m^3 with great variability among decades (Table 1.5). Although average annual harvest volume in 1990's was much higher than other decades, it still amounted to only a fifth of AAC during that decade (Table 1.5).

Birch and aspen are minor harvested species compared to white spruce in the study area. A total of 93,792 m^3 birch and 10,728 m^3 of aspen have been harvested from state forest lands during the study period, which represent an average of about 1% or lower of AAC volume (Table 1.5). However, birch harvest volume has increased in the most recent years (Table 1.5), reflecting increased interest in wood biomass energy (Fresco and Chapin 2009a, b). Wood biomass is renewable energy, which can mitigate climate change as long as the net carbon emissions of the wood energy harvest and is less than fossil fuels displaced, and that biomass harvest does not cause a reduction in long term forest productivity. Wood biomass can also stimulate local economies, especially in rural Alaska, by decreasing dependence on imported fuel and creating local employment. Based strictly on the perspective of the relationship of volume of removals versus growth across the analysis area as a whole, the current low-level of birch and aspen harvest suggests that birch and aspen harvest for biomass energy can be significantly expanded in our analysis area.

Although AAC figures are available for Toghotthele land, harvested volume cannot be compared directly to the AAC by species because harvested volume on Toghotthele land was only recorded as an aggregate number for all species (Table 1.6). Nevertheless, some inferences can be made from the data. On Toghotthele land, aggregate harvested volume for all species was less than the AAC of the white spruce sawlog category alone (based on inventory volume), a situation similar to state forest lands. These data indicate that historical white spruce sawlog harvest levels are sustainable in terms of wood production on Toghotthele ownership (Table 1.6). However, the harvest volume was greatly underestimated because of missing data from more than half of the harvested area (Table 1.4). The harvest units that do not have volume data were logged in 1976, 1979, or 1981. The missing data is an issue of record keeping during this time period due to land transfers from federal ownership to Native Corporations. As a result, it is possible that harvested volume might have exceeded AAC in these early decades. Harvest records for Toghotthele land are complete from 1990 to 2012, and the harvest volume was below the AAC during that time (Table 1.6). Overall, these private forest land owners were most interested in obtaining revenue from their timber at an early date and in selling when market prices were perceived to be highest, while minimizing costs, rather than planning a regular or predictable schedule of timber sales.

Access is one of the biggest constraints in forest harvest management in the study area (Wurtz et al. 2006). As a results, harvest activity was concentrated on the road-accessible portion of state forest lands, even though harvest level as a whole was below AAC. Only 15.3% of state forest lands are within 1 km of a road (Table 1.7), but 67.4% of the harvested area and 75.2% of all harvest units fall within 1 km of a road (Table 1.8). Nearly all of the harvested area (91.2%) and the harvest units (95.5%) occurred within 4 km of a road (Table 1.8). The total area of harvest was greatest near Fairbanks on state forest lands. Because this greater harvest activity produced a denser network of roads, the forest was more accessible, and the highest concentration of harvest near roads occurred there (Table 1.8). Although the forest type previous to harvest is not fully documented, during the period of analysis (1972-2012) the overwhelming majority of harvest on state forest lands occurred in mature white spruce stands. As a result, a comparison of growth versus area harvested as a basis for considering sustainability in our study area largely applies to that type.

Across all state forest lands the calculated area equivalent of AAC (volume) for mature white spruce types is 449 ha. The actual average area harvested (any type) per year on state forest lands was 240 ha, which represents 53.5% of the area equivalent of the AAC for mature white spruce. The average area harvested within 1 km of the 2013 road network was 202 $ha \cdot yr^{-1}$. Because the area of mature white spruce within 1 km of a road is 32.6% of the total area of mature white spruce on all state forest lands (Table 1.7), an equivalent proportion of white spruce AAC would amount to 146 $ha \cdot yr^{-1}$. Based on this calculation, the historical harvest (all stand types) near the road network was 1.4 times higher than the area equivalent of the AAC for mature white spruce within that zone. The historical harvest within 2, 3, and 4 km of a road were 105%, 91%, and 84% of the mature white spruce AAC area within those zones, respectively. Although it appears that harvest level in the areas within 2 km of roads is higher than AAC area, a few qualifications apply to these figures.

The actual harvest included a few hardwood dominant stands, so not all harvested activity removed the mature white spruce type. Historically, harvest activity began and has been concentrated in the most productive part of the forest as a whole. As a result, the growth rate of regeneration in the harvest units might be higher than a forest-wide average of trees of the same age. In the study area, harvested stands initially dominated by hardwood reproduction can become mature white spruce eventually, especially aspen stands which often contain a white spruce component (Figure 1.7). Also, as the road system expands, new stands will be added to the area within 1 km of roads, and the rate of future harvest in the earlier (2013) area near roads can be reduced if the harvest level stays about the same or lower. Finally, annual area burned (Alaska Interagency Coordination Center 2015) or disturbed by insect outbreaks (Werner et al. 2006) in Alaska has increased significantly in the past few decades, so it cannot be assumed that all harvested stands would have survived natural disturbance for the past 40 years. Within state forest land, 255,448 ha are included in the mapped perimeters of areas burned from 1972 to 2012 (Alaska Interagency Coordination Center 2015). A significant portion of the harvested area (21%) in the Fairbanks management area during the period of analysis occurred in fire-killed and associated insect-killed spruce, and as a result the harvest program *per se* was not primarily responsible for those reductions in the mature spruce type (see section 1.5.4).

1.5.4. Evolution of Harvest Methods

During the study period from 1972 to 2012, the most common harvesting methods on state forest lands were clearcutting and select cutting for white spruce in white spruce-dominated forest (Figure 1.8). Until the early-1980s, select cutting for spruce was the dominant harvest method used on state forest lands (Figure 1.8). The major harvest method then shifted from select cutting to clearcut salvage logging, due to the Rosie Creek Fire in 1983 (Figure 1.8), which burned 3,500 ha of state forest. The priority after this fire was to salvage killed or injured trees to recoup valuable timber before decay, and to prevent the spread of insect outbreaks from injured to healthy trees (Juday 1985). A total of approximately 1,200 ha was salvage logged due to the fire. Across all state forest lands the total white spruce fuelwood volume harvested in the last 40 years is only 78,050 m^3, and nearly half of that volume came from salvage logging in the late-1980s and 1990s.

In 1990s, as salvage logging from the 1983 fire was being completed, clearcutting increased rapidly in response to increased wood demand for export (Figure 1.8). However, the scale of clearcutting in the study area was small compared to other boreal regions where large-scale, widespread clearcutting with individual harvest units exceeding 100 ha has been used for wood production (Burton et al. 2006; Larsson and Danell 2001; Timoney and Peterson 1996). The mean area of harvested blocks (continuous harvest area within a given year) in the study area was mostly under 10 ha, except for few peaks in the 1970's and 1995 (Figure 1.9). This harvest block figure includes not only clearcutting, but also various partial cutting treatments. In Interior Alaska, only 6 out of 687 harvest blocks in the Fairbanks area, 1 out of 33 in the Kantishna area, and 6 out of 36 in Toghotthele Native Corporation land exceeded 100 ha. Ten out of 13 of these large harvest blocks were logged in the 1960's and 1970's, when area of harvest was overestimated (see Methods). It is apparent that the ecological effects of clearcutting in the study area are likely to be smaller than much of the remainder of the North American boreal forest because of the small size of Alaska clearcuts compared to other regions that have experienced much more extensive and sustained clearcutting.

In many boreal regions, homogenous forest created by extensive clearcutting and planting is subject to management efforts to restore heterogeneous forest structures and a diversity of species habitats (Cyr et al. 2009). Partial cutting is one of the management practices used to restore forest diversity. In the late 1990s, such concerns along with decreasing demand resulted in a shift in the major harvest method from clearcutting to partial cutting on state forest lands (Figure 1.8). Various partial cutting methods, particularly species selection cut of white spruce and birch, were adopted and increasingly applied as clearcutting decreased (Figure 1.8). Partial cutting techniques have been the predominant harvest method since then (Figure 1.8).

On other forest lands, the specific harvest method used before 1992 is mostly unknown (Figure 1.10). In those harvest units that do contain a record of harvest method on this ownership type, clearcutting and various partial cutting techniques were used (Figure 1.10). Clearcutting was used slightly more than partial cutting.

1.5.5. Site Preparation

In Interior Alaska, mechanical site preparation, involving either scarifying or trenching, is sometimes applied following harvest to enhance seedbed quality and reduce competitive species for white spruce (Cole et al. 2003; Youngblood and Zasada 1991). Depth of organic layer is one of the most important factors determining post-disturbance natural regeneration in Interior Alaska (Haeussler et al. 2002; Johnstone and Kasischke 2005). Removing the organic layer promotes establishment of new vegetation by exposing a mineral soil substrate that many species require for successful germination (Haeussler et al. 2002; Johnstone and Kasischke 2005). Removing the organic layer also reduces remaining vegetation which compete with tree regeneration (Haeussler et al. 2002; Johnstone and Kasischke 2005). Species competing with white spruce, especially *Calamagrostis canadensis*, spread rapidly by below-ground rhizomes after disturbance (Lieffers et al. 1993). White spruce, on the other hand, regenerates only from seed, and grows slower than most other early successional tree species (Nienstaedt and Zasada 1990). As a result, removing the organic layer and below-ground rhizomes of competitive species helps enhance white spruce regeneration.

Although managing the residual organic layer following harvest is known to assist white spruce establishment, site preparation was applied only on a limited scale in the study area (Table 1.3). Site preparation on state forest lands was most actively used in 1980s and 1990s when total harvest area increased (Figure 1.11), while site preparation was only used before 1980 on other forest lands (Figure 1.11). Although prescribed burning and herbicide application are major site preparation methods used in many forest regions (Granstrom 2001; Wagner et al. 2004), prescribed burning and the application of herbicide have only been used for experimental purposes during the study period in central Interior Alaska (Youngblood et al. 2011).

1.5.6. Reforestation

Although site preparation can improve some factors limiting white spruce regeneration, white spruce regeneration is limited by factors in addition to seedbed conditions (Nienstaedt and Zasada 1990). Large white spruce seed crops need two years of optimal weather conditions for abundant cone production and therefore occur only about every 10 years (Juday et al. 2003;

Roland et al. 2014; Zasada 1985). Moreover, white spruce seeds must be dispersed by wind from live parent trees, and in all but exceptional cases large numbers of seeds only fall within 100 to 150 m of the source (Youngblood and Max 1992). Site preparation alone cannot solve these issues of timing and distance to seed source in natural white spruce regeneration. As a result, foresters generally have relied on planted seedlings when assisted spruce regeneration is required (Figure 1.12a), even though planting seedlings is more expensive than site preparation. In the study area, white spruce seeds are collected locally in large white spruce seed crop years and sent to a nursery (Alaska Division of Forestry 2000). Seedlings are grown in the nursery and predominantly one year-old seedlings are planted. As a result, planting seedlings is by far the most expensive regeneration practice in boreal Alaska forest harvest management. In addition, carbon footprint of seedling production and planting is large. Direct planting of white spruce seeds was applied on three harvest units on state forest lands and one unit on other forest lands.

Artificial reforestation on state forest lands was rarely used until the early 1980s, but increased greatly after the mid-1980s, particularly because of the large harvested area created by the Rosie Creek Fire and associated salvage and sanitation logging (Juday 1985; Figure 1.12a). Until around 2000, white spruce seedlings were planted in most state harvest areas, but in the most recent 15 years of the analysis period, the amount of artificial reforestation decreased (Figure 1.12a). On other forest lands, artificial reforestation was used on more than half the area harvested after 1990 (Figure 1.12b).

Some introduced species were planted experimentally at a very limited scale in the Fairbanks management area, including lodgepole pine (*Pinus contorta*), Siberian larch (*Larix sibirica*), and Scotch pine (*Pinus sylvestris* L.). In this management area, out of the total 3,223 ha planted, 74 ha (2.3%) were planted with introduced species exclusively, and 162 ha (5%) were planted with mixed white spruce and introduced species. Introduced species are of interest for a number of reasons. One of the introduced species, lodgepole pine, grows fastest in the first part of its life span (Alden and Zasada 1983; Alden 1988), and can be used for short-rotation harvest for firewood. Other issues that motivated experimentation with introduced species include concerns about susceptibility of native species to spruce bark beetle, larch sawfly, and reduced growth of white spruce due to drought stress caused by climate warming (Barber et al. 2000).

1.5.7. An Integrated Perspective on Harvest Methods, Site Preparation, and Reforestation

On state forest lands, the most common set of post-harvest management practices were natural regeneration with no site preparation (~62% of area harvested, Figure 1.13a). On other forest lands, the most common post-harvest practices were site preparation and/or planting of spruce (~64%, Figure 1.13b). Site preparation on state forest lands often was applied following salvage logging (> 1/3 of salvage logged area), but rarely following select cutting for spruce/birch or following partial cutting (Figure 1.13a). Species select cutting and partial cutting leave residual stems in the stand, causing technical challenges for the operation of heavy equipment required for site preparation. Site preparation on state forest lands was used mainly to reduce vegetative competition with planted seedlings, not primarily to prepare seedbeds for natural seedfall. As a result, site preparation was almost always followed by planting of white spruce seedlings (Figure 1.13a). However, on other forest lands, site preparation was used alone (without planting) in the majority of cases (Figure 1.13b).

Artificial reforestation was applied more often following clearcutting than other harvest methods on state forest lands (Figure 1.13a). Artificial reforestation was applied on about half the area of clearcuts on state forest lands (Figure 1.13a), particularly because of the increased harvest activities of the 1990s (Figure 1.8). Clearcutting increased in the 1990s along with increased log export demand, which stimulated post-harvest regeneration practices as a result (Figure 1.8 and 1.11a).

1.6. Synthesis and Conclusions

This study examined levels and types of historical harvest management, which provides a useful basis for sustainable timber production, although many other aspects affect sustainability, such as wildlife habitats, carbon sequestration, and economic factors. Rapid climate change is a relatively new challenge in sustainable timber production, but knowledge of past harvest activities provides insights for possible adaptations for future harvest and regeneration management.

In central Interior Alaska, forest harvest management was low-input and heavily relied on natural regeneration. The primary reasons for the low-input management are distance from major market, limited access, low product value, and high cost of labor (Wurtz et al. 2006). A comparison of harvest and growth levels indicate the potential to expand forest harvest sustainably, particularly because of the large magnitude of difference between the low harvest volume and the much higher established annual allowable cut levels (Table 1.6). This opportunity for increased harvest is in contrast to other forest regions where a new ecological or sustainability emphasis requires modification of previous forest management practices and often a reduction in harvest level. However, in boreal Alaska the great majority of the harvest activity has occurred near the limited areas of road-accessible land (Table 1.8). A concentration of management effects on areas the public has greatest access to increases the potential for conflict over forest uses. The management of state and private forest lands analyzed in this study is primarily focused on sustainable production of wood[2]. Existing policies[3] call for fish and wildlife habitat values to be identified and accommodated through a process of interagency consultation and negotiation to the degree that they do not seriously detract from the wood production program. Obviously expanded harvest and continued harvest of particular forest types could cause reductions in wildlife habitat of some species valued by the public to a greater degree than has been experienced in forest management to date.

In central Interior Alaska, forest production and management activity over the past 40 years were strongly focused on white spruce harvest and assisted regeneration of white spruce (Figure 1.4). Until recently, the harvest of mature white spruce was the principal source of profit. However, the increasing demand for woody biomass for energy generation potentially could make the harvest of other species and the use of other harvest methods more feasible, especially an increase in Alaska birch and aspen harvest. Even so, recent experience with biomass demand demonstrates that white spruce is preferred.

Currently, the volume of birch and aspen harvest represents only 1% and 0.2% of the allowable cut on average, respectively (Table 1.6). Alaska birch and aspen regenerates more successfully and grows faster than white spruce in Interior Alaska boreal forest (Morimoto et al. 2016; Youngblood 1995). These growth characteristics of birch and aspen reduce the area required to sustain harvest volume in a biomass production system compared to a spruce-based system, especially if projected rotation ages as low as 70 years are adopted (Hanson 2013). In

[2] Alaska Forest Resources & Practices Act Sec. 41.17.200 (a). The booklet is available at http://forestry.alaska.gov/Assets/uploads/DNRPublic/forestry/pdfs/forestpractices/PDF_Forest_Resources_and_Practices_Act_text-May_2013_update.pdf

[3] Alaska Forest Management Statutes & Regulations Sec. 16.14.871. The booklet is available at http://forestry.alaska.gov/Assets/uploads/DNRPublic/forestry/pdfs/statutes/2013_For_mgmt_stat_reg_TEXT_COVER_UPDATE.pdf

addition, birch and aspen regeneration does not face the same limitations as white spruce natural regeneration, such as infrequent large and/or viable cone crops (Nienstaedt and Zasada 1990; Roland et al. 2014). Moreover, increasing the harvest of birch and aspen could reduce the demand for mature white spruce for biomass energy, reducing the historical focus on white spruce harvest within the accessible land base. Industrial hardwood harvest generally has not been commercially profitable because there are few facilities that utilize hardwood or small diameter wood, although local fuelwood demand is high, accessible high volume birch stands can generate values similar to white spruce. This study demonstrates that birch and aspen harvest can be greatly expanded in a sustainable manner, and that therefore it may be practical to invest in facilities that utilize birch and aspen. Additional study of economic limitations and opportunities is a priority for sustainable timber management in the study area.

However, there are uncertainties regarding hardwood harvest in central Interior Alaska. Because the amount of hardwood harvest to date has been small, regeneration following hardwood harvest is not well studied. Although hardwood regeneration following white spruce harvest is rapid and abundant (Morimoto et al. 2016), birch regeneration following harvest of mature birch stands appears to face some challenges. Foresters in the study region frequently must contend with a thick cover of *Calamagrostis canadensis* that develops following harvest of birch stands (Packee 1990), which suppresses tree regeneration. Site preparation, which can be used to remove competitive vegetation, has been evaluated experimentally following harvest (Cole et al. 1999; Youngblood et al. 2011). However, site preparation seldom has been used following birch harvest, so its potential to deal with suppression of regeneration by *Calamagrostis* still remains to be fully evaluated. Site preparation largely has been used following spruce harvest to prepare for planting white spruce seedlings on state forest lands.

However, site preparation can be used alone (without planting spruce seedlings) to create desirable seedbed and remove competitive vegetation for white spruce regeneration depending on the timing and the management goal. Examples are when large spruce seed crops are present or expected within a few years after harvest, or the management goal can be achieved without immediate or rapid regeneration of white spruce. Finally, site preparation with natural regeneration may have cost advantages over planting of white spruce seedlings.

Our analyses suggest that forest harvesting in central Interior Alaska can be expanded in a sustainable manner if harvest activities are distributed geographically and by species in a way that prevents reduction of forest productivity or loss of ecological services. Although harvest activity historically was concentrated on the road-accessible area and in the mature white spruce type, the overall harvest level since 1972 was much smaller than the upper limit for sustainable productivity. Even in the zone closest to the road network, harvest area did not greatly exceed the sustainable level. Wildland fire has been suppressed moderately effectively on the portion of state forest lands managed for wood production, so if an expanded harvest is planned appropriately at the landscape scale, the harvest could even affect the fire-protected boreal forest ecosystem positively by emulating natural fire disturbance, assuming continuation of the historical fire regime.

In general, continued study of the evolution of harvest levels versus growth and inventory will be required to provide the necessary information to address sustainability issues, particularly for the developing stands harvested over the past 40 years. Complete and precise recording of harvest activities and transparency of the data (e.g. open access) will be critical. In addition to sustained wood yield, many other values and perspectives, such as wildlife habitat, carbon sequestration, and social values need to be considered for sustainable forest management.

Nonetheless, this study provides a first synthesis view of some of the basic information inputs needed to develop sustainable timber program.

Our analysis suggests a couple of available options to expand timber production while providing for sustained yield of forest products. The first option is an expansion of the road network to provide access to additional stands containing mature white spruce. The second option would be a shift in harvest and utilization from white spruce to other species, especially birch and aspen. There are two potential areas that could provide increased harvest, and they both contain a large amount of white spruce, birch, and aspen (Figure 1.14a-c). Area 1 is in the Kantishna area, and area 2 is north part of the Fairbanks area. Although the area 1 is remote from the existing road system, potentially it could be accessed by river in winter. Mature white spruce occurs mostly along the river, but extensive road construction would be required for birch and aspen harvest in the area 1. Area 2 contains a large area of birch-dominated stands.

Finally, if it is assumed that road access will not increase significantly and replacement of equivalent forest stand types and ages to those harvested is the goal, then (1) a modest reduction of AAC level for the mature white spruce type in particular, and (2) a limitation of harvest area or adjustment of AAC volume level by zones according to distance from road would be required. Such adjustments would be focused on meeting primarily environmental sustainability goals.

1.7. Acknowledgements

This research was funded by a project BAK LAP (Boreal Alaska – Learning, Adaptation, Production) supported by appropriation to the Alaska Department of Natural Resources Division of Forestry, the McIntire Stennis Cooperative Forestry Research Program (ALK13-04), and the Bonanza Creek Long-Term Ecological Research program funded by the National Science

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1.9. Figures

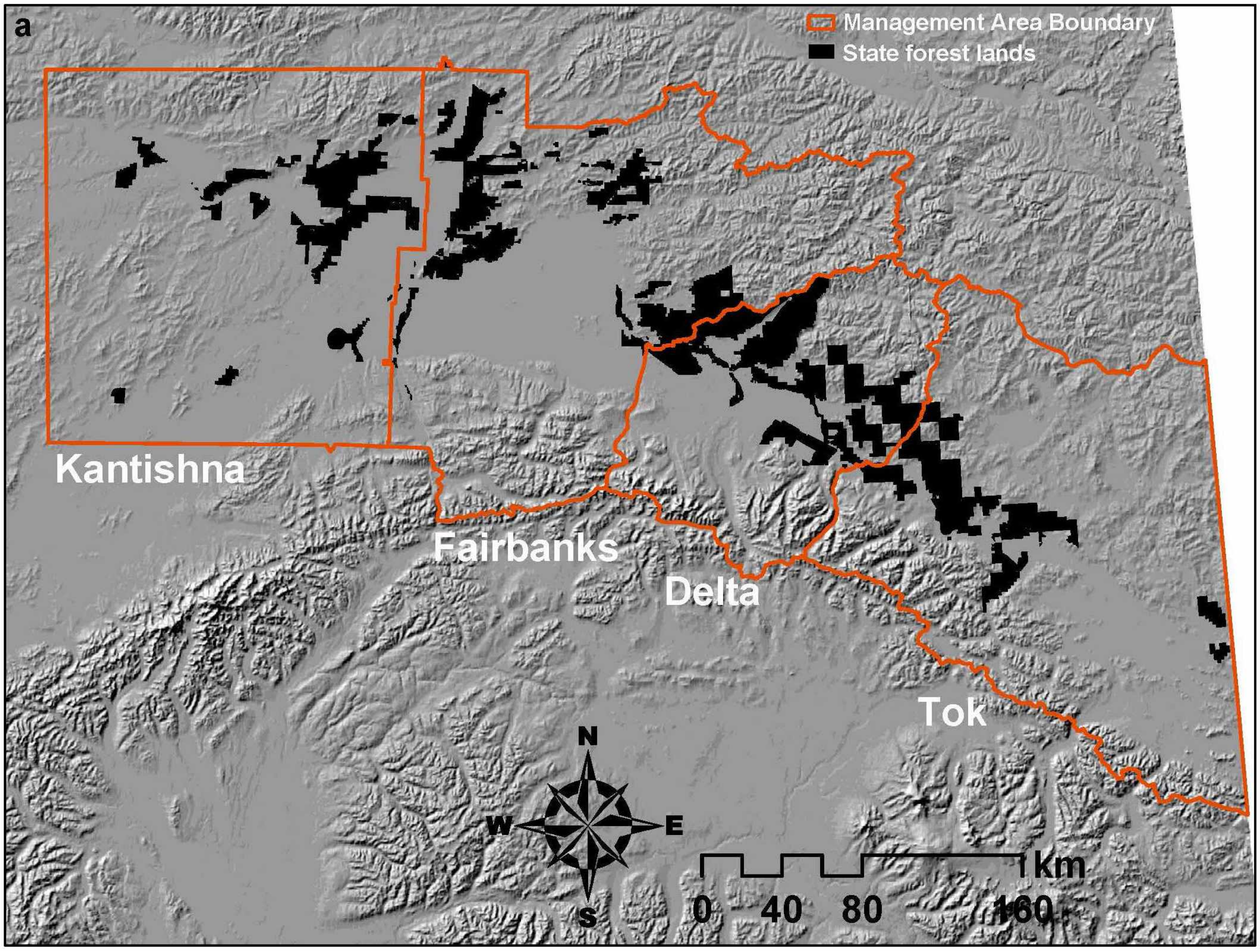
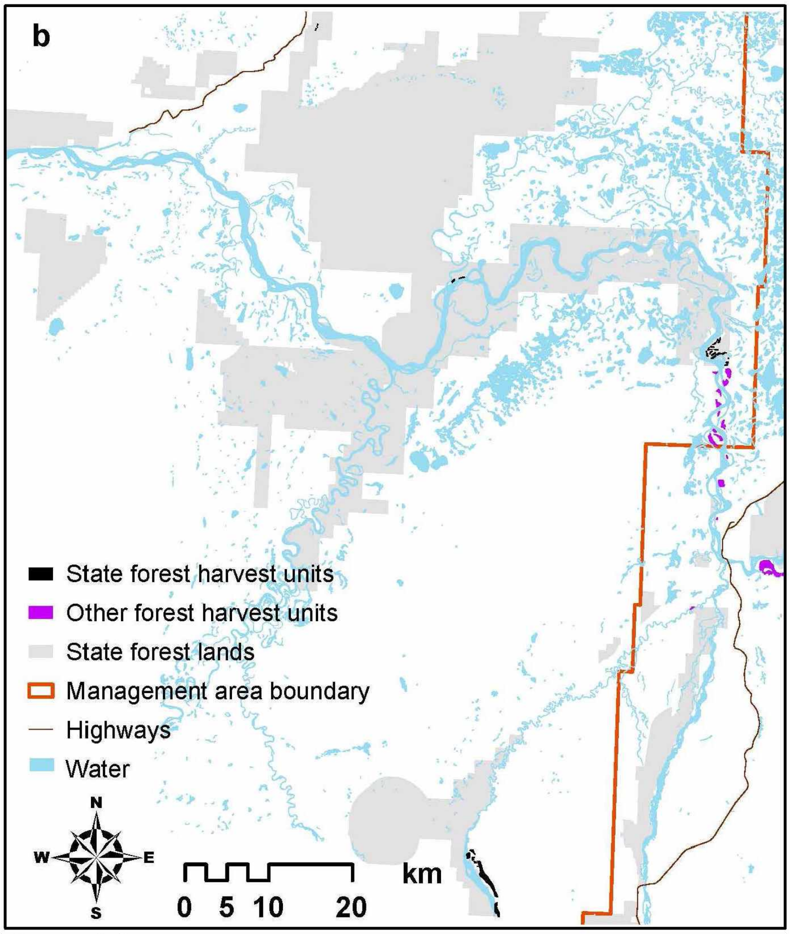


Figure 1.1 Maps of study area. (a) Study area is within the Tanana Valley of the Interior Alaska boreal region (dashed boundary). The productive forest in the area is managed by Alaska Department of Natural Resources, Division of Forestry (AKDOF). There are two classes of state land including the Tanana Valley State Forest (TVSF) and other state "forest classified" lands (black polygons as state forest lands) which are administered within four management areas: Fairbanks, Kantishna, Delta, and Tok (orange boundaries). Historical forest harvest units in (b) Kantishna, (c) Fairbanks, (d) Delta, and (e) Tok Management Area.



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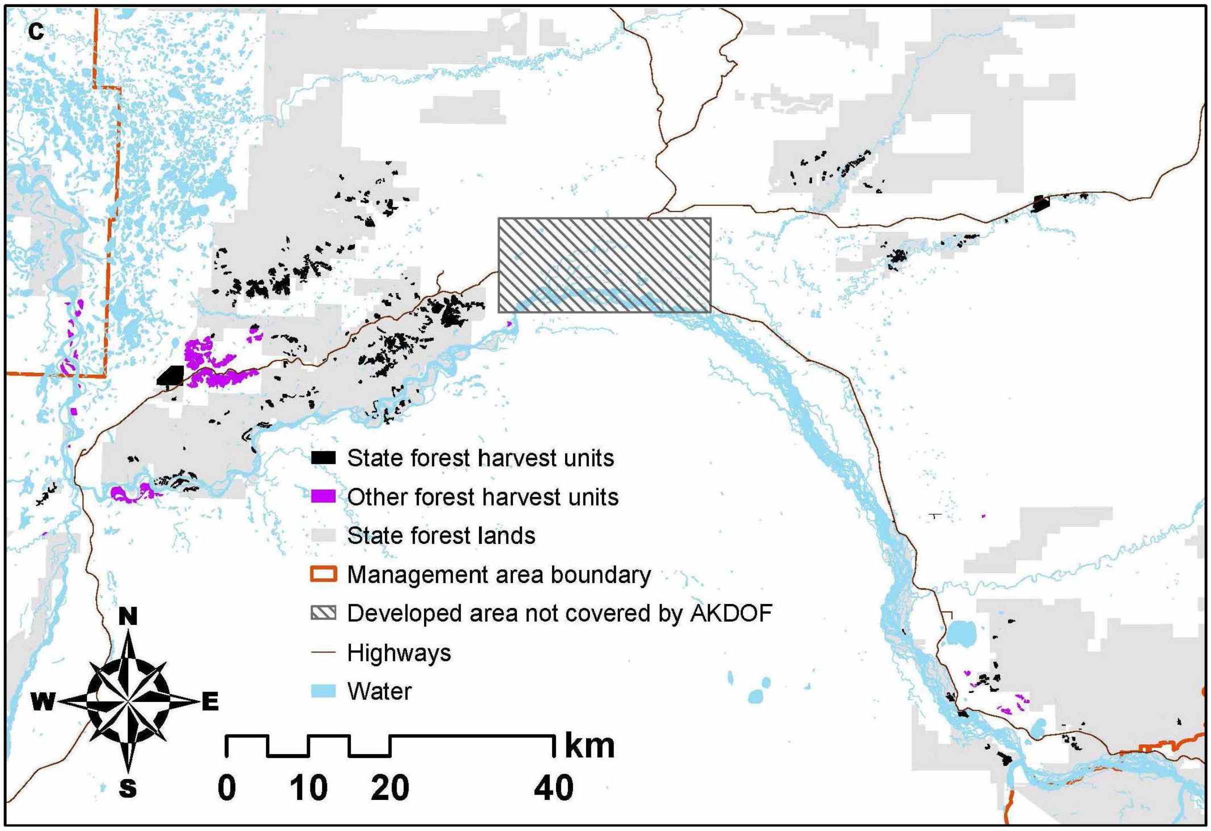

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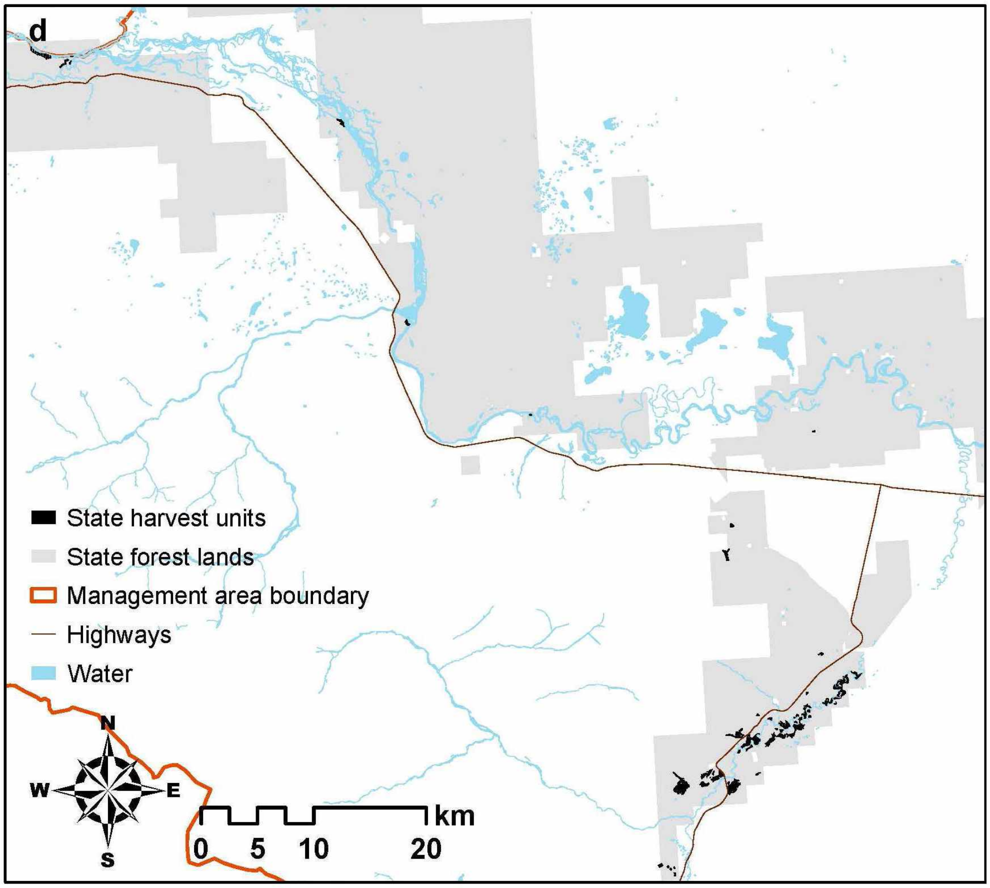

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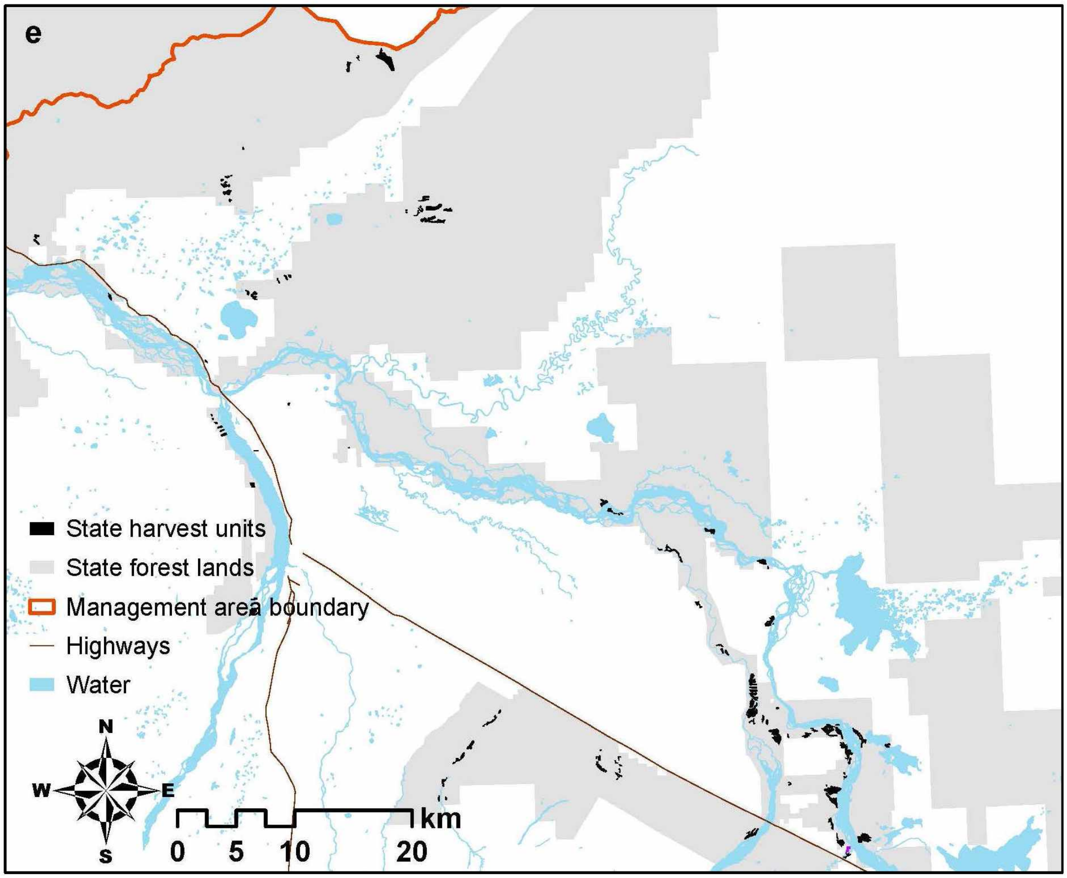

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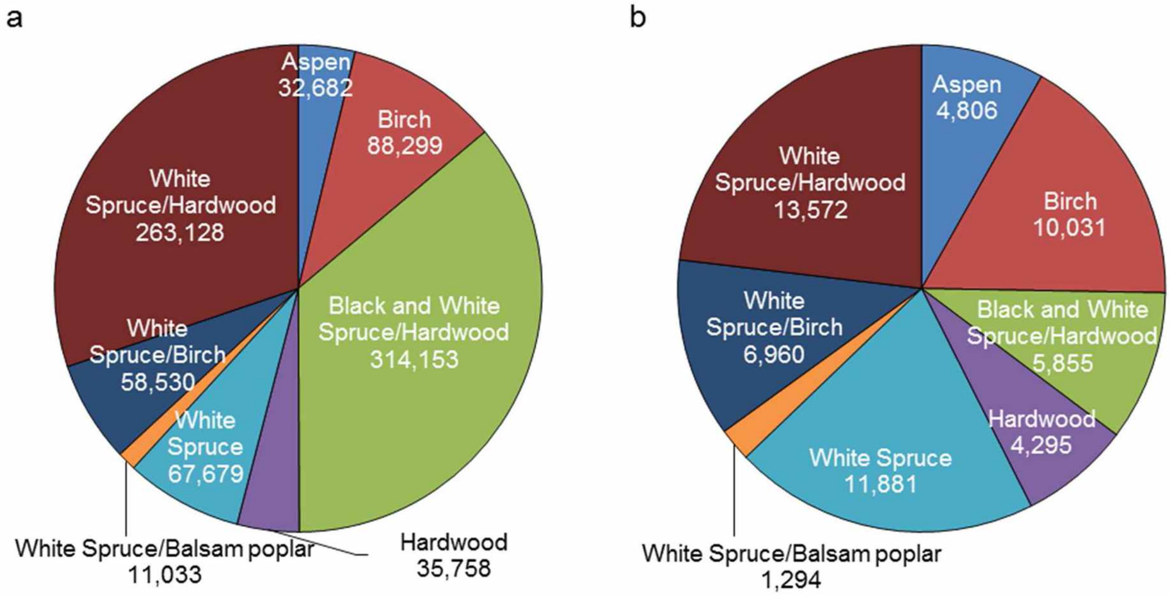

Figure 1.2 Major forest cover types on state forest lands in terms of (a) area (ha) and (b) volume (1000 m^3).

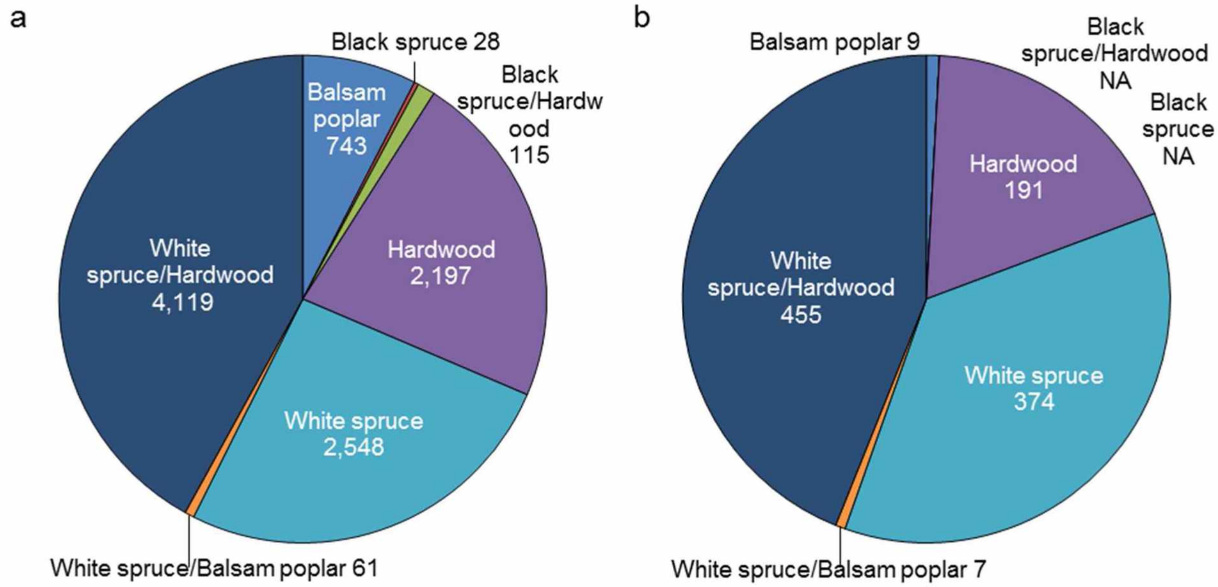

Figure 1.3 Major forest cover types on Toghotthele Native Corporation lands in terms of (a) area (ha) and (b) volume (1000 m^3).

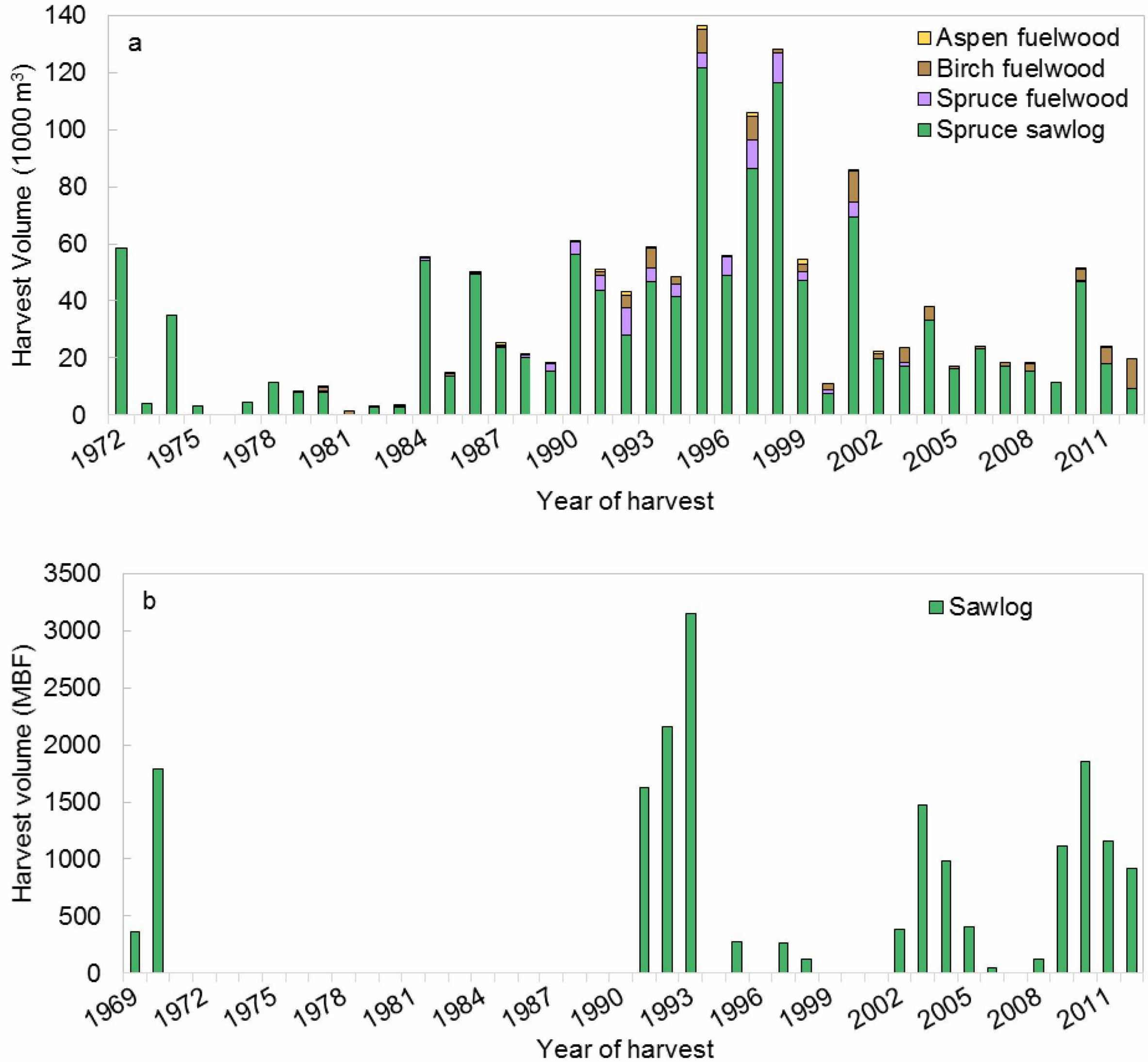

Figure 1.4 Annual harvest volume (a) on state forest lands by products from 1972 to 2012 (m^3), and (b) on other forest lands from 1969 to 2012 (MBF).

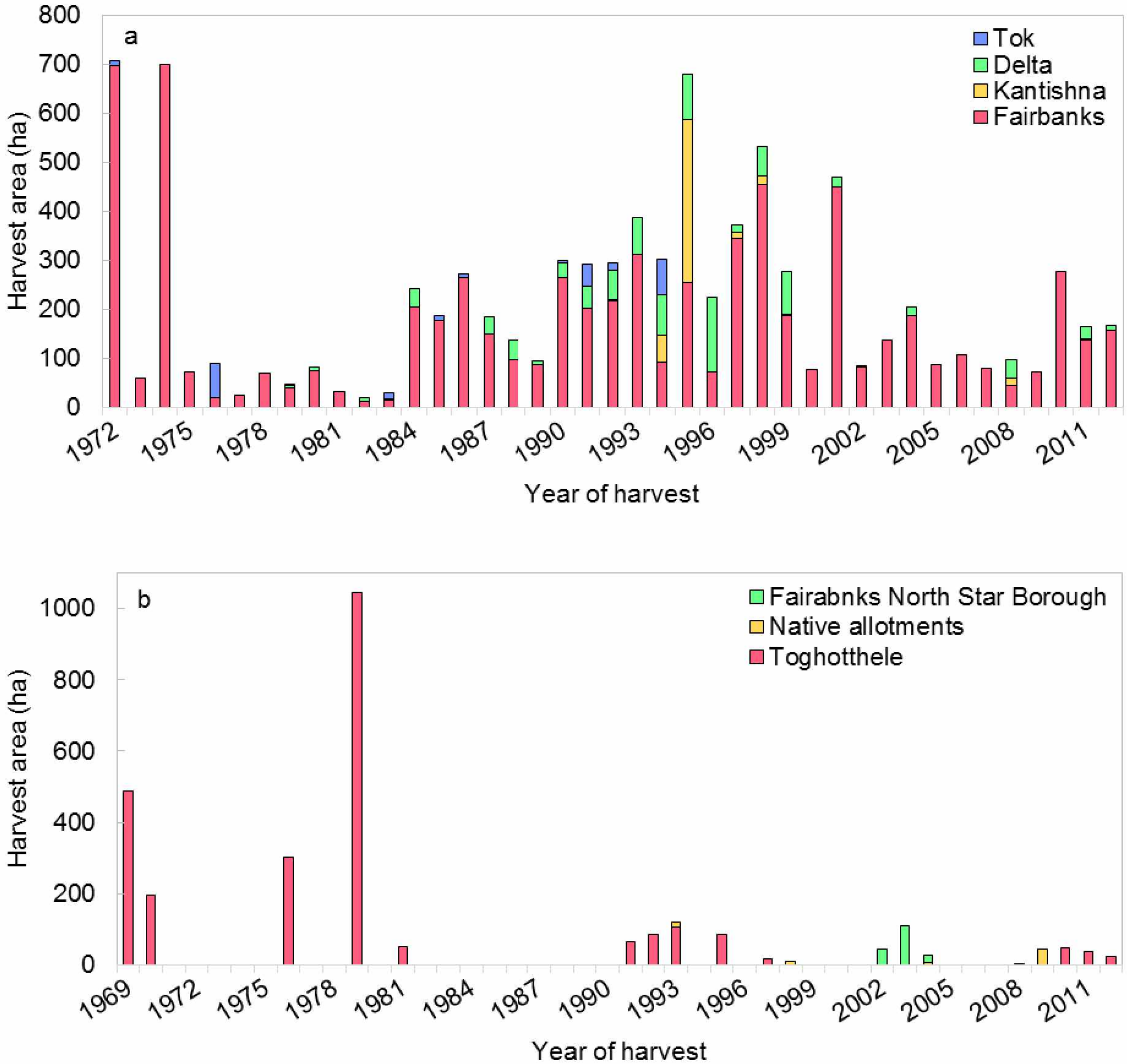

Figure 1.5 (a) Annual forest harvest area (ha) by management areas on state forest lands from 1972 to 2012, and (b) by ownership on other forest lands from 1969 to 2012.

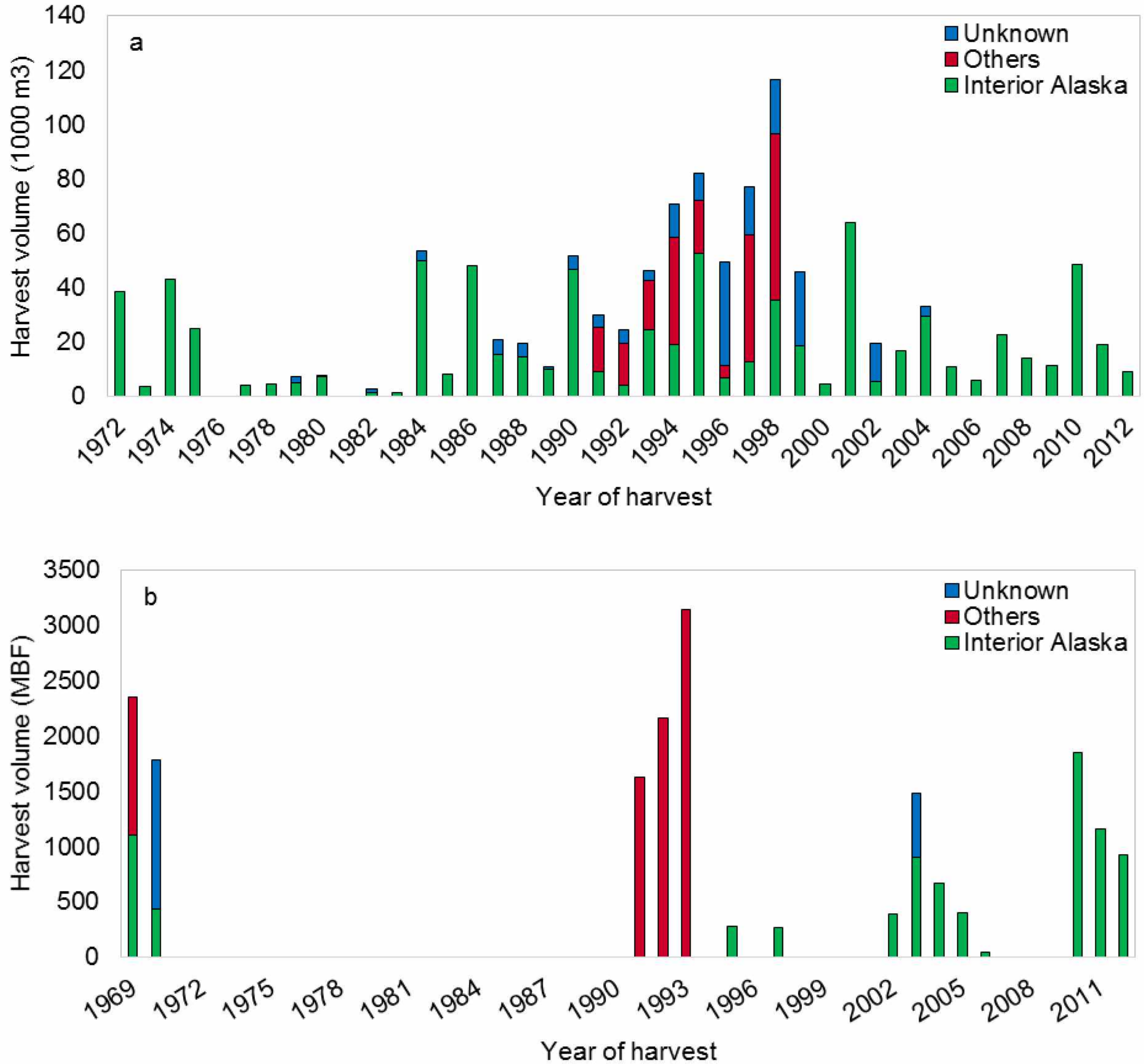

Figure 1.6 Annual white spruce sawlog harvest volume by purchaser on (a) state forest land (m3) and (b) other forest land (MBF).

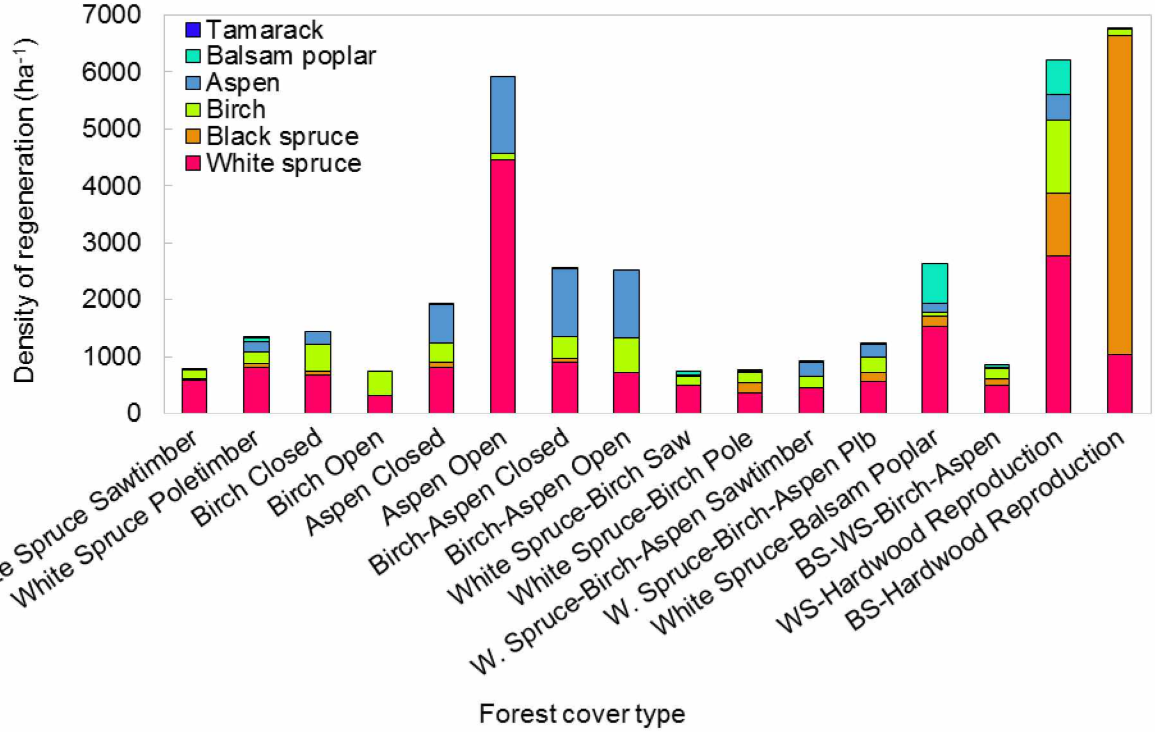

Figure 1.7 Density of seedlings and saplings (DBH < 5 inch) on major forest cover types by species (ha^{-1}).

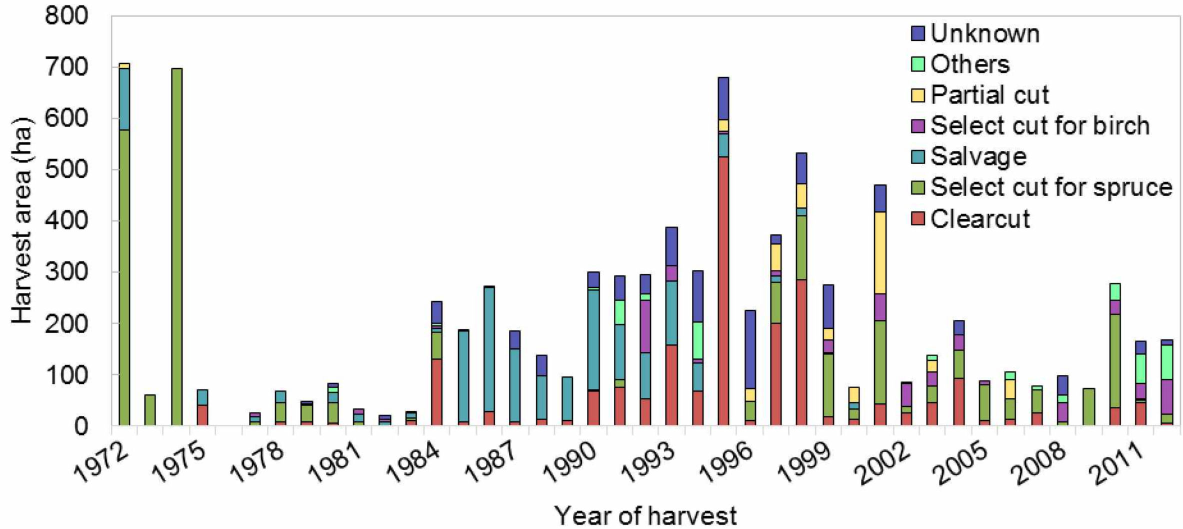

Figure 1.8 Annual harvest area (ha) by harvest methods on state forest lands from 1972 to 2012.

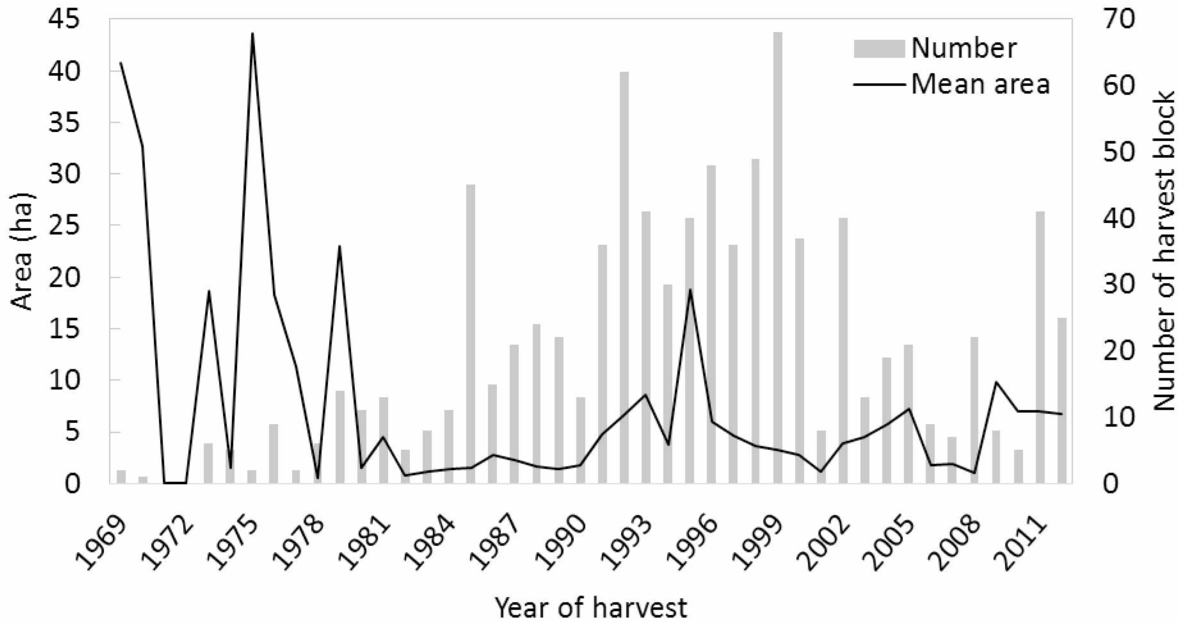

Figure 1.9 Mean area and number of harvest blocks (continuous area of harvest) on combined state and other forest lands from 1969 to 2012.

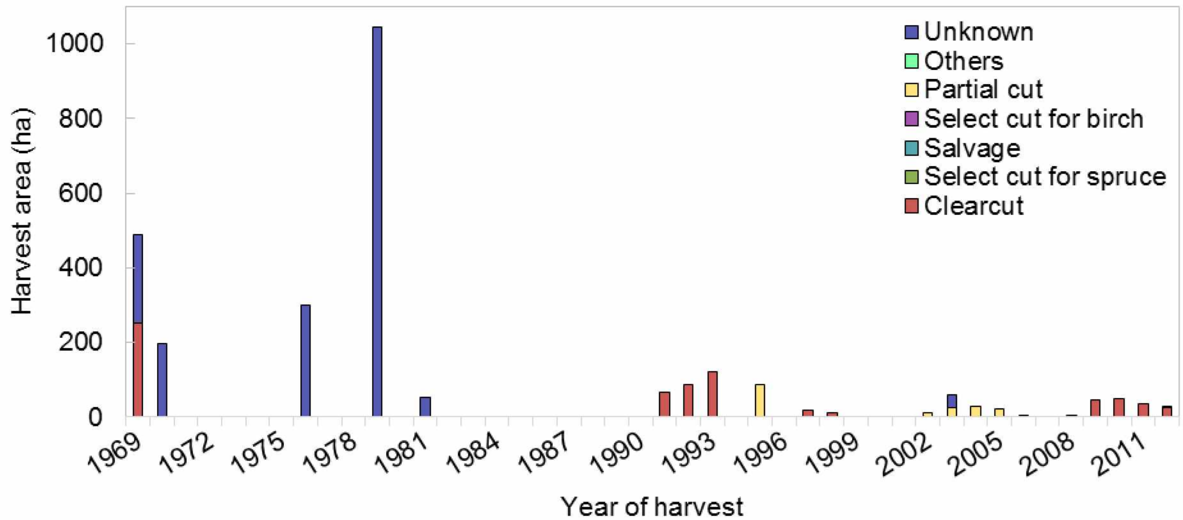

Figure 1.10 Annual harvest area (ha) by harvest methods on other forest lands from 1969 to 2012.

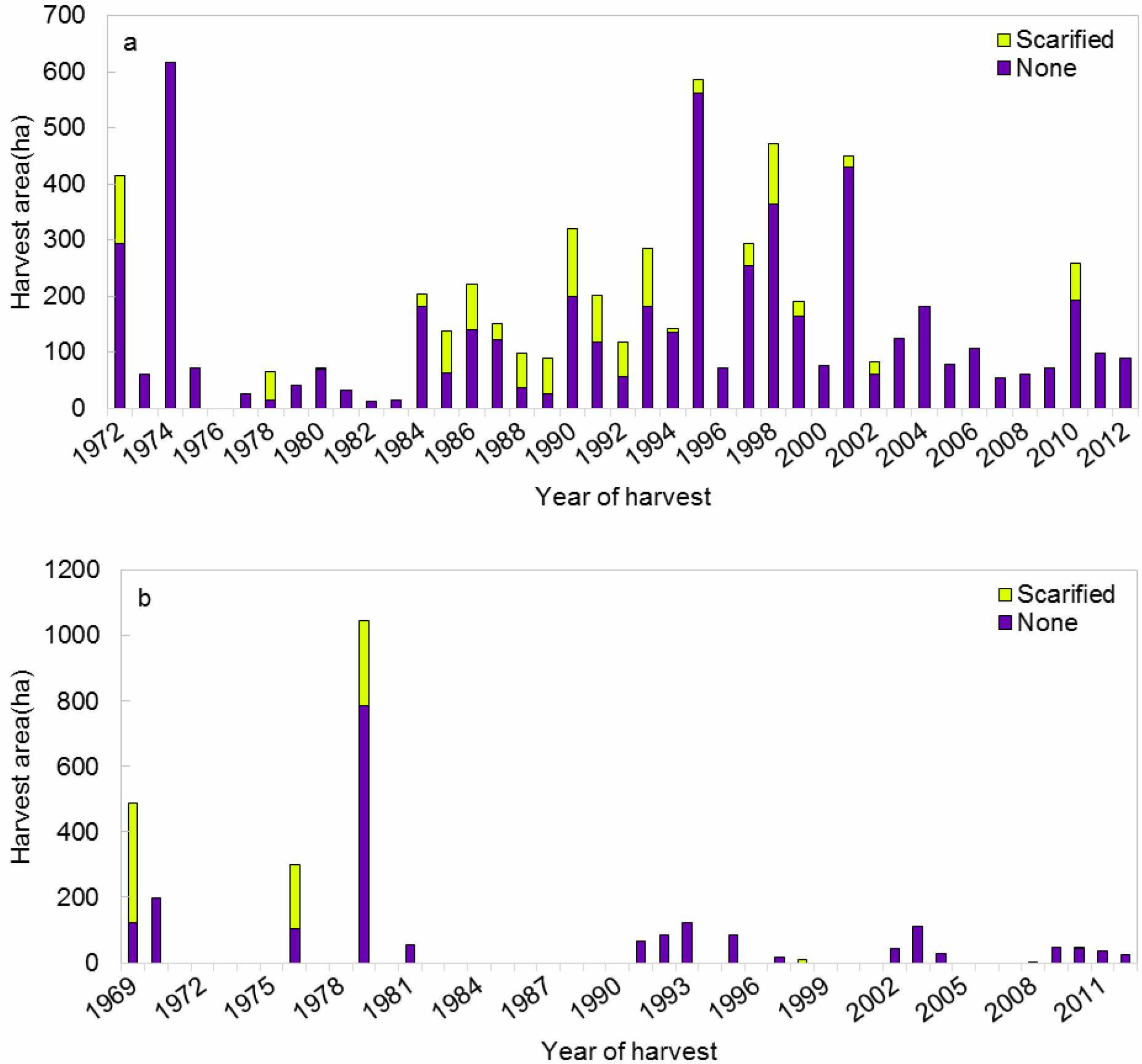

Figure 1.11 Annual harvest area (ha) by site preparation methods on (a) state forest lands from 1972 to 2012, and (b) other forest lands from 1969 to 2012.

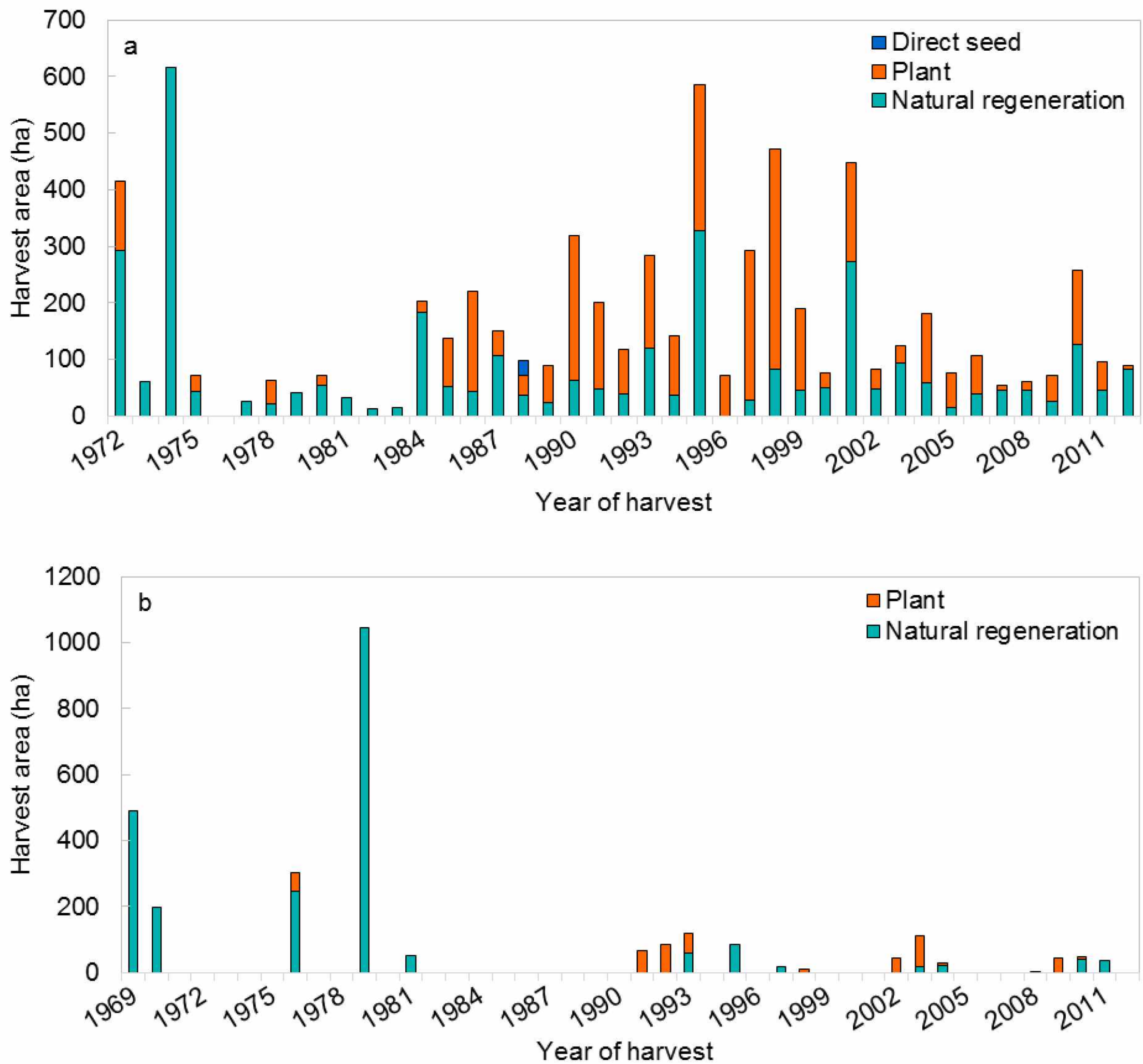

Figure 1.12 Annual harvest area (ha) by reforestation methods on (a) state forest lands from 1972 to 2012, and (b) other forest lands from 1969 to 2012. Reforestation data were not available for the Delta and Tok management area of state forest lands.

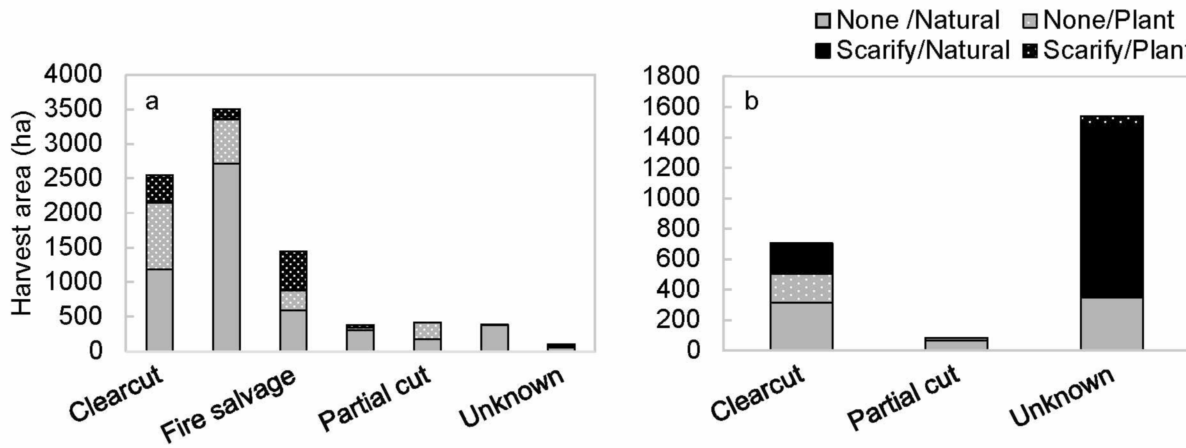

Figure 1.13 Harvest area (ha) by the combination of management practices (a) on state forest lands, and (b) on other forest lands.

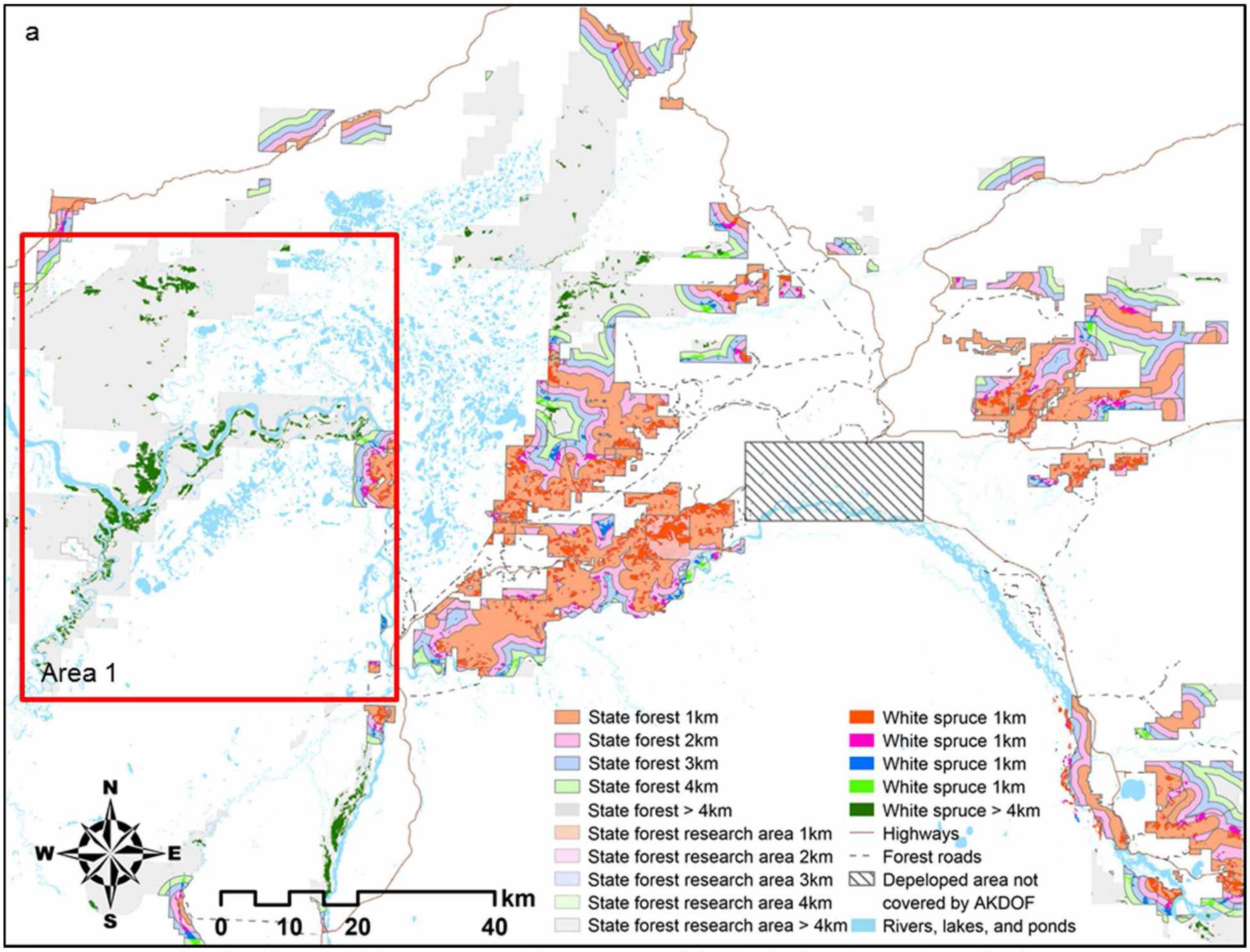

Figure 1.14 Distribution of (a) mature white spruce, (b) birch dominated, and (c) aspen dominated stands in zones within 1, 2, 3, 4, and >4 km of road network. Birch dominated stands include mixed birch-aspen stands as well.

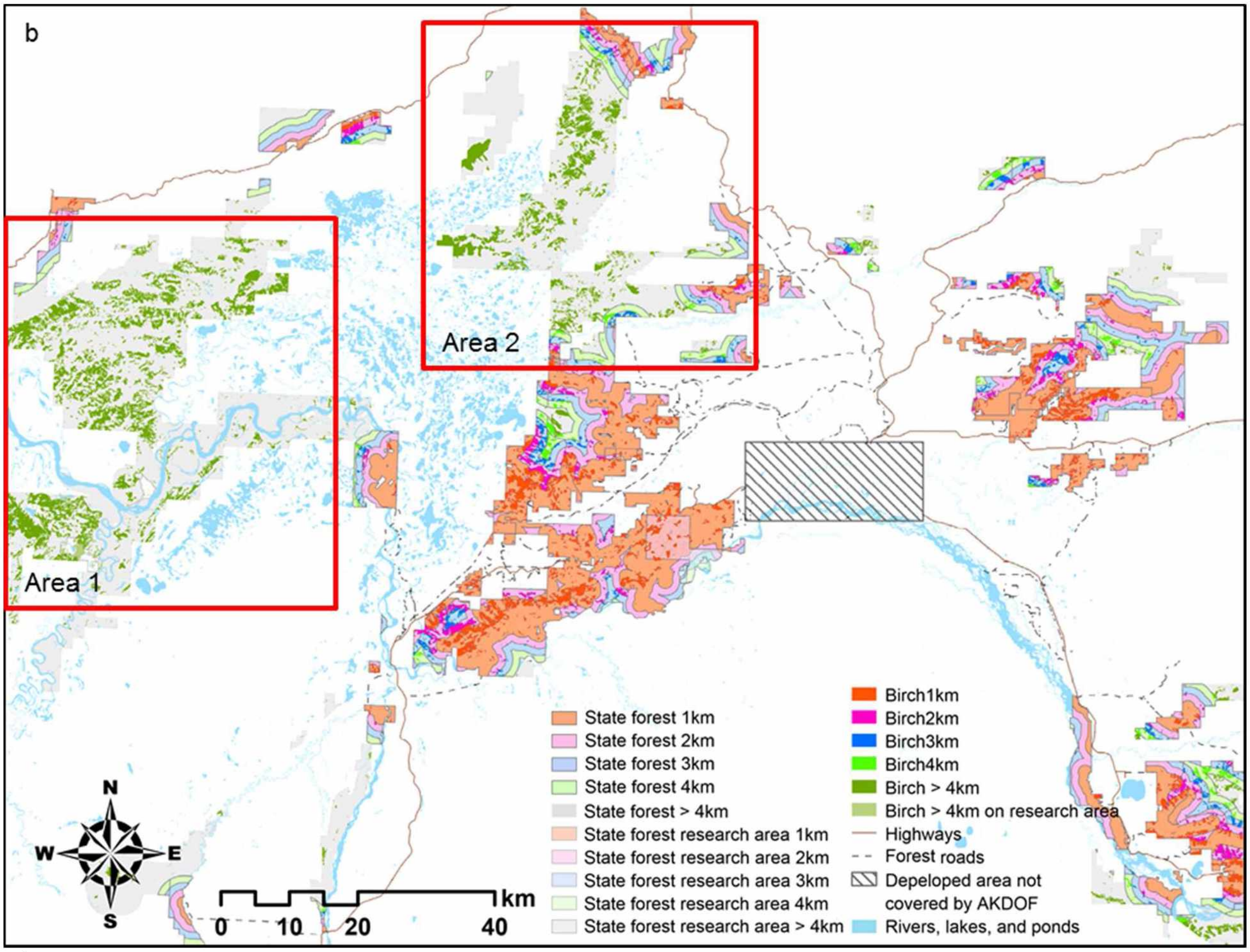

Figure 1.14 cont.

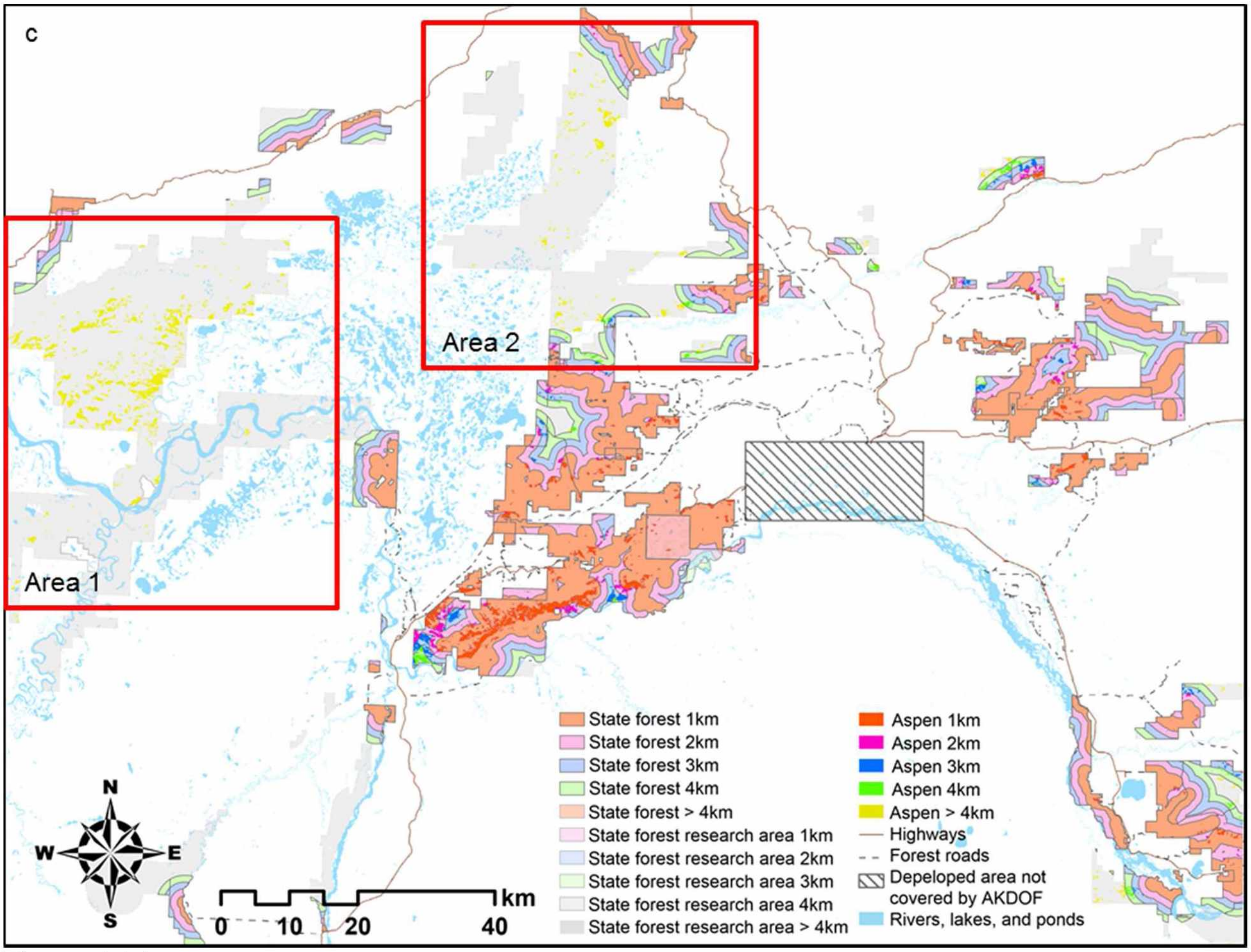

Figure 1.14 cont.

1.10. Tables

Table 1.1 Area of the land, timberland, and volume of wood on state and other forest lands. Data was only available for Toghotthele Native Corporation lands for other forest. MCF = 1000 cubic foot and MBF = 1000 board foot (Hanson 2013).

			Total Net Volume		
Management area	Area (ha)	Timberland (ha)	Cubic Foot (MCF)	Cubic Meter (m^3)	Board Foot (MBF)
State forest					
Kantishna	230,397	177,348	431,486	12,218,323	806,820
Fairbanks	348,178	256,284	699,571	19,809,645	1,480,844
Delta	344,686	258,919	637,537	18,053,037	1,297,644
Tok	239,498	178,712	304,165	8,612,994	472,199
Totals	1,162,760	871,263	2,072,759	58,693,999	4,057,506
Non-state forest					
Toghotthele	52,277	12,805	36,888	1,045	105,647

Table 1.2 Harvest type classification based on the harvest types identified in the databases obtained from Alaska Division of Forestry and Tanana Chiefs Conference.

Classified harvest types	Fairbanks, Kantishna, Delta	Tok	Toghotthele	Native allotments	FNSB
Clearcut	Clearcut	NA	Clear Cut; clearcut; clearcut with reserves	Clearcut	Patch retention
Select cut for spruce	Select cut for spruce	NA	NA	NA	NA
Salvage logging	Fire salvage; Salvage	FIRE SALVAGE			
Select cut for birch	Select cut for birch	NA	NA	NA	NA
Partial cut	Partial cut/dead&drying spruce only; Partial cut/diameter limit; Partial cut/leave tree birch 50' spacing	HABITAT-IMPROVEMENT HARVEST; WIND FALL SALVAGE	individual tree selection	Diameter Limit	9" diameter limit
Others	Clear ROW for birch; River salvage; Select cut for aspen; Select cut for aspen and birch; Select cut for birch and spruce; Select cut for spruce and optional birch; Select cut for spruce, fuel from ROW; Select cut for spruce, rest ROW; Select for br, rest on ROW; Select for sp, fuel in ROW; Select for sp, others select for br	PATCH HARVEST; SELECT CUT; SELECTIVE; STIP HARVEST; STRIP HARVEST	NA	NA	NA
Unknown	Null	Null	Null	Null	Null

Table 1.3 Timberland and harvested area (ha) in the study area for the period of 1972 to 2012.

		Harvested Area (ha)		
	Timberland (ha)	Harvest	Site preparation	Reforestation
State forest				
Fairbanks	256,284	7,120	1,185	3,223
Kantishna	177,348	436	0	103
Delta	258,919	1,637	NA	NA
Tok	178,712	1,780	NA	NA
State total	871,263	10,973	1,185	3,326
Other forest				
Toghotthele	12,805	2,560	831	260
FNSB	NA	234	0	137
Native allotment	NA	80	10	80
Other total	12,805	2,873	841	476
Total	884,067	13,846	2,026	3,802

Table 1.4 Area (ha) and the number of harvest unit that contain harvested volume data in each management areas during the study period.

	Harvest area (ha)		Number of harvest units	
	with volume data	without volume data	with volume data	without volume data
State forest				
Fairbanks	7,080	51	737	12
Kantishna	436	0	35	0
Delta	953	622	144	88
Tok	252	638	34	137
State forest total	8,721	1,311	950	237
Other forest				
Toghotthele	2,864	3,462	36	38
FNSB	31	0	18	0
Native allotments	80	0	6	0
Other forest total	2,974	3,462	60	38
TOTAL	11,695	4,774	1,010	275

Table 1.5 The relationship between annual allowable cut (m^3) and average harvested volume (m^3) by decades and overall from 1972 to 2012 for each management area within state forest lands.

		AAC (m^3)	Average annual harvested volume (m^3)					% of AAC
			1972-1980	1981-1990	1991-2000	2001-2012	Overall	
Fairbanks	Spruce	105,328	14,663	22,387	38,558	21,602	24,406	23.2%
	Birch	75,056	139	413	3,501	4,077	2,179	2.9%
	Aspen	40,071	0	144	548	150	215	0.5%
Kantishna	Spruce	68,603	0	0	9,091	348	2,319	3.4%
	Birch	48,886	0	0	70	0	17	0.0%
	Aspen	26,100	0	0	0	7	2	0.0%
Delta	Spruce	89,959	289	2,236	14,942	3,360	5,493	6.1%
	Birch	64,104	0	0	330	0	97	0.2%
	Aspen	34,224	0	29	165	0	57	0.2%
Tok	Spruce	64,868	NA	NA	NA	NA	NA	NA
	Birch	7,752	NA	NA	NA	NA	NA	NA
	Aspen	4,818	NA	NA	NA	NA	NA	NA
TOTAL	Spruce	328,757	14,952	24,623	62,591	25,310	32,218	10.9%
	Birch	195,798	139	413	3,901	4,077	2,293	1.0%
	Aspen	105,213	0	173	713	157	274	0.2%

Table 1.6 Annual allowable cut (MBF) and average annual harvested volume (MBF) by decades and overall from 1972 to 2012 in Toghotthele Native Corporation lands. Although annual allowable cut was calculated for each harvest products, harvested volume was only available as a combined volume of all products.

	Annual allowable cut (MBF)		Aggregate average annual harvested volume (MBF)				
			1969-1980	1981-1990	1991-2000	2001-2012	Overall
Toghotthle	Spruce sawlog	760					
	Spruce pole	2,488	179	0	748	328	308
	Birch pole	2,573					

Table 1.7 Accessibility of all state forest lands by area of forest type.

	State forest lands area (ha)				
To road	≤ 1 km	≤ 2 km	≤ 3 km	≤ 4 km	Any distance
State forest lands	177,921	288,671	372,436	435,078	1,163,033
Excluding research area	172,798	282,386	365,095	427,158	1,152,602
Unharvested	42,071	63,517	77,815	86,134	198,360
Mature white spruce	20,831	28,969	34,545	37,403	61,509
Birch dominant	21,240	34,548	43,270	48,731	136,851

Table 1.8 Accessibility of harvested state forest lands within management areas shown by total area and number of harvest units.

	Forest harvested area (ha)					Number of forest harvest units				
To road	≤ 1 km	≤ 2 km	≤ 3 km	≤ 4 km	Any distance	≤ 1 km	≤ 2 km	≤ 3 km	≤ 4 km	Any distance
Fairbanks	6,701	6,814	6,834	6,834	7,120	730	735	736	736	736
Kantishna	247	317	349	360	436	24	30	30	31	33
Delta	797	1,028	1,216	1,286	1,390	143	178	183	189	203
Tok	548	746	836	836	890	80	116	130	130	137
TOTAL	8,293	8,905	9,235	9,316	9,836	977	1,059	1,079	1,086	1,109

1.11. Appendices

Appendix 1.1 Forest Management Database for timber sales in the Fairbanks, Kantishna, and Delta management areas of state forest

Column name	Description	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
SALE_NUMBE	Sale number	NC-XXX
SALE_UNIT	Sale unit	NC-XXX-ZZ
ADL_NUMBER	Alaska Division of Land tracking number	Numeric
PURCHASER	Purchaser	Text
Remarks	Notes	Text
DATE_SOLD	Date of sale	MM/DD/YYYY
EXPIRATION	Date of expiration	MM/DD/YYYY
TERM_DATE	Date of termination	MM/DD/YYYY
NEGOTIATED	Type of sale	N; Y; blank
AVG_VAL_SC	Average value of saw component	Dollar
AVG_VAL_FC	Average value of fuelwood component	Dollar
SAW_CCF	Harvest volume of sawlog	ccf
FUEL_CCF	Harvest volume of fuelwood	ccf
SAW_CCF_AC	Harvest volume of sawlog	$ccf \cdot ac^{-1}$
FUEL_CCF_A	Harvest volume of fuelwood	$ccf \cdot ac^{-1}$
SALE_VOL_C	Total Harvest volume of sale	ccf
BIRCH_VOL	Harvest volume of birch	ccf
SP_FUEL_VO	Harvest volume of spruce fuelwood	ccf
ASPEN_VOL	Harvest volume of aspen	ccf
SOLD_FOR	Sale price	Dollar
TOTAL_VALU	Total value of sale	Dollar
IMPROVE_	Development cost (roads etc)	Dollar
SALE_BOND	Bond for performance	Dollar
ROAD_BOND	Bond for project work	Dollar
SALE_NAME	Name of sale	Text

Appendix 1.1 cont.

Column name	Description	Unit/categories
HARVEST_TY	Type of harvest	Clear ROW for birch; Clearcut; Clearcut / Land Use Conversion; Fire salvage; Partial cut/dead&drying spruce only; Partial cut/diameter limit; Partial cut/leave tree birch 50' spacing; River salvage; Road Easement Cutting of 66 ft wide; Salvage; Select cut for aspen; Select cut for aspen and birch; Select cut for birch; Select cut for birch and spruce; Select cut for spruce; Select cut for spruce and cottonwood; Select cut for spruce and optional birch; Select cut for spruce, fuel from ROW; Select cut for spruce, rest ROW; Select for spruce; Select for br, rest in ROW; Select for sp, fuel in ROW; Select for sp, others select for br; Thinning; Blank
Unit	Unit number	Numeric
STATUS	Sale status	Active; Proposed; OTC (on the contract); Reoffer; Terminated; Blank
Acreage	Size of harvest	Acres
Sale_year	Year of sale	Numeric
Species_1	Harvest species	Birch; Spruce; Blank
Management_Block	Management area	Fairbank; Knatishna; Delta
Management_Unit	Management unit	Text
Area_Plan	Management plan	TBAP; TBAP & TVSF; TVSF,TBAP; TVSF/TBAP; Blank
Species_2	Harvest species	Aspen; Birch; Mixed; Spruce; Spruce fuel; Blank
LEGAL_DESCRIPTION	Legal description	Sections, township, range
TOWNSHIP	Township	Text
RANGE	Rage	Text
SECTIONS	Section	Numeric
Bidders		Numeric
SHAPE_Length	Perimeter of polygon	m
SHAPE_Area	Size of polygon (harvest unit)	m^2

Appendix 1.2 Forest Management Database for reforestation in the Fairbanks and Kantishna management areas of state forest

Column	Description	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
SUBCLASS	class of shape file	POLY (polygon)
SALE_NUMBER	Sale number	NC-XXX
SALE_UNIT	Sale unit	NC-XXX-ZZ
Unit	Unit	ZZ
PLANT_UNIT	Plant unit	NC-XXX-YYa
LOGGED_DATE	Date of harvest	MM/DD/YYYY
SITE_PREP	Method of site preparation	None; blank; Blade; Blacke; Disc trench; Plow; Shear blade
PREP_DATE	Date of site preparation	MM/DD/YYYY
COST_AC_SC	Cost of scarification	Dollar
REGEN_METH	Method of reforestation	Blank; Natural seed; Natural seed + replant; Plant; Plant + replant; Direct seed
YEAR_REGEN	Year of artificial reforestation	Numeric
REGEN_SPEC	Species used for artificial reforestation	Spruce; Lodgepole; S. Larch
REGEN_SP_1	Additional species used for artificial reforestation	Aspen; Larch; Lodgepole; Scotch pine
REGEN_SP_2	Additional species used for artificial reforestation	Larch
SEEDLOT	Seedlot for regeneration species	Text
SEEDLOT2	Seedlot for additional regeneration species	Text
SEEDLOT3	Seedlot for additional regeneration species	Text
CONTRACTOR	Planting contractor	Text
CONTRACT_A	Contract award number for planting contractor	Numeric
COST_PER_T	Cost per tree	Dollar
SPACING	Spacing of planting	Foot
TREES_AC	Number of trees planted per acre	Numeric
PLUG_TYPE	Type of plug	313B; 6-L; R-L; STYRO313B
TREE_AGE	Age of planted planting tree	Numeric
TREE_SOURC	Source of planted tree	K&C; PELTON; PRT; STATE; blank
COLD_STORA	Cold storage of seedlings	N; Y; blank
START_DATE	Start date of artificial regeneration	MM/DD/YYYY
END_DATE	End date of artificial regeneration	MM/DD/YYYY

Appendix 1.2 cont.

Column	Description	Unit/categories
WEATHER	Weather	CLEAR, WARM; COLD; COOL; DRY; GOOD; HOT; OVERCAST; SMOKEY; WET; WET, COOL; blank
TEMP	Temperature	F
REL_HUM	Relative humidity	No records
WIND_SPD	Wind speed	No records
CLOUD_COV	Cloud cover	No records
SOIL_TEMP	Soil temperature	No records
SOIL_MOIS	Soil moisture	No records
REGEN_ACR	Area of regeneration	acre
DATE_SURVEY	Date of regeneration survey	MM/DD/YYYY
NB_of_PLOTS	Number of survey plots	Numeric
STOCK_LOCA	Total percentage stocking (Number of stocked plots/total number of plots)	%
PERC_PL_WS	Percent of planted white spruce	%
PERC_NAT_WS	Percent of natural white spruce	%
PERC_TOT_WS	Percent of total white spruce	%
PERC_NAT_BI	Percent of natural birch	%
PERC_NAT_AS	Percent of natural aspen	%
PERC_NAT_BS	Percent of natural black spruce	%
PERC_NAT_BP	Percnet of natural balsam poplar	%
PERC_PL_PI	Percent of planted lodgepole pine	%
PERC_PL_LA	Percent of planted siberian larch	%
STOCK_NB_TREE	Percent of regeneration standard	%
NB_TOTAL_TREE	Number of total tree	Numeric
NB_PL_WS	Number of planted white spruce	Numeric
NB_NAT_WS	Number of natural white spruce	Numeric
NB_TOT_WS	Number of total white spruce	Numeric
NB_NAT_BI	Number of natural birch	Numeric
NB_NAT_AS	Number of natural aspen	Numeric
NB_NAT_BS	Number of natural black spruce	Numeric
NB_NAT_BP	Number of natural balsam poplar	Numeric
NB_PL_PI	Number of planted lodgepole pine	Numeric
NB_PL_LA	Number of planted siberian larch	Numeric
SHAPE_Length	Perimeter of polygon	m
SHAPE_Area	Area of polygon (reforestation unit)	m^2
OBSERVATION	Notes	Text
STOCK_450	Percent of regeneration standard	%
total_acres	Area of unit	acre

Appendix 1.3 Forest Management Database for timber sales in the Tok management area of state forest

Column names	Descriptions	Unit/categories
OBJECTID	id assigned by ArcGIS	numeric
STRATUM	Forest cover stratum	No records
VEG_CLASS	Vegetation class	No records
SIZE_CLASS	Size class	No records
DENSITY_CL	Density class	No records
DESCRIPT	Description	No records
ACRES	Area of harvest	acre
SUBCLASS		No records
SALE_NUMBE	Sale number	Incomplete
SALE_UNIT	Sale unit	"DP-XX"; "NC-XX"; "NCP-XX"
ADL_NUMBER	Alaska Division of Land tracking number	Numeric
PURCHASER	Purchaser	No records
TOWNSHIP	Township	No records
RANGE	Rage	No records
SECTIONS	Section	No records
DATE_SOLD	Date of sale	MM/DD/YYYY
EXPIRATION	Date of expiration	MM/DD/YYYY
TERM_DATE	Date of termination	No records
NEGOTIATED	Type of sale	No records
AVG_VAL_SC	Average value of saw component	No records
AVG_VAL_FC	Average value of fuelwood component	No records
SAW_CCF	Harvest volume of sawlog	No records
FUEL_CCF	Harvest volume of fuelwood	No records
SAW_CCF_AC	Harvest volume of sawlog	$ccf \cdot ac^{-1}$
FUEL_CCF_A	Harvest volume of fuelwood	No records
SALE_VOL_C	Total harvest volume of sale	No records
BIRCH_VOL	Harvest volume of birch	No records
SP_FUEL_VO	Harvest volume of spruce fuelwood	No records
ASPEN_VOL	Harvest volume of aspen	No records
SOLD_FOR	Sale price	No records
TOTAL_VALU	Total value of sale	No records
IMPROVE_	Development cost (roads etc)	No records
SALE_BOND	Bond for performance	No records
ROAD_BOND	Bond for project	No records
SALE_NAME	Name of sale	

Appendix 1.3 cont.

Column names	Descriptions	Unit/categories
HARVEST_TY	Harvest type	"FIRE SALVAGE"; "HABITAT IMPROVEMENT HARVEST"; "PATCH HARVEST"; "SELECT CUT"; "SELECTIVE"; "STRIP HARVEST"; "WIND FALL SALVAGE"
Shape_Leng	Perimeter of polygon	m
Shape_Area	Area of polygon	m^2

Appendix 1.4 Forest Management Database for timber sales in Toghotthele Native Corporation land

Column	Description	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
AREA	Area of harvest	m^2
PERIMETER	Perimeter of harvest	m
LOGUNIT	Unit of harvest	Text
LOGYEAR	Year of harvest	Numeric
ACREAGE	Area of harvest	Acre
status	Status of sale	"active"; "closed"
Purchaser	Purchaser	Text
AVG_VAL_SC	Average value of saw component	Dollar
AVG_VAL_FC	Average value of fuelwood component	Dollar
SAW_MBF	Harvest volume of sawlog	mbf
FUEL_CCF	Harvest volume of fuelwood	ccf
SAW_MBF_ACRE	Harvest volume of sawlog	$mbf·ha^{-1}$
FUEL_CCF_ACRE	Harvest volume of fuelwood	$ccf·ha^{-1}$
PRI_SPECIES	Primary species	"Spruce"; blank
PRI_PRODUCT	Primary product	"Sawtimber"; blank
SEC_SPECIES	Secondary species	No records
SEC_PRODUCT	Secondary product	No records
SOLD_FOR	Sold price	Dollar
PROJECT_VAL	Development cost	Dollar
HARVEST_TYPE	Type of harvest	"Clear Cut"; "clearcut"; "clearcut with reserves"; "individual tree selection"
Notes	Notes	Text
sale_name	Name of sale	Text
Shape_Length	Perimeter of polygon	m
Shape_Area	Area of polygon	m^2

Appendix 1.5 Forest Management Database for reforestation in Toghotthele Native Corporation land

Column names	Descriptions	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
reforestation_type	Reforestation method	"active sale"; "natural"; "planted"
Regen_year	Year of reforestation	Numeric
year_logged	Year of harvest	Numeric
site_prep_method	Site preparation method	"hand scalp"; "scarified"; "scarified 25% each acre"
operator	Operator of reforestation	Text
unit	Reforestation unit	Text
Nursery	Nursery of planted seedlings	Text
Notes	Notes	Text
acres	Area of reforestation	acre
SHAPE_Length	Perimeter of polygon	m
SHAPE_Area	Area of polygon	m^2

Appendix 1.6 Forest Management Database for timber sale and reforestation in Native allotments

Column names	Descriptions	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
Allotment_Nu	Allotment number	AKF xxx; AKFF xxx
Allottee	Person who was allotted the land	Text
Year_logged	Year of harvest	Numeric
BF_volume	Harvest volume	BF
CF_volume	Harvest volume	CF
Contractor	Contractor	Text
Acres	Area of harvest	acre
reforestation_tech	Reforestation method	Plant; Spot Scarify / direct seed
Reforestation_year	Year of reforestation	1993-2010
harvest_tech	Harvest type	Clearcut; Diameter Limit
Shape_Length	Perimeter of polygon	m
Shape_Area	Area of polygon	m^2
notes	notes	Text

Appendix 1.7 Forest Management Database for timber sales in Fairbanks North Star Borough lands

Column names	Descriptions	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
Comment	Notes	Text
Corr_Type	GPS correction type	"Differential"; blank
Rcvr_Type	GPS recovery type	"Pro XR"; blank
GPS_Date	Date of GPS record	MM/DD/YYYY
GPS_Time	Time of GPS record	HH:MM:SS
GPS_Area	Area	acre
GPS_Perime	Perimeter	m
acres	Area of harvest	acre
Name	Name of harvest	Text
Unit	Harvest unit	Numeric
purchaser	Purchaser of harvest	Text
sold_for	Sale price	Dollar
volume_MBF	Harves volume	mbf
Volume_CCF	Harves volume	ccf
price_per_MBF	Sale price	Dollar mbf-1
price_per_CCF	Sale price	Dollar ccf-1
date_sold	Sold date	MM/DD/YYYY
stumpage_bond	Bond for performance	Dollar
project_bond	Bond for project	Dollar
date_harvest_complete	Date of harvest completed	MM/DD/YYYY
Harvest_Method	Harvest type	"9" diameter limit"; "clearcut with resserves"; "patch retention"; "seed tree"
status	Status of harvest	"Active"; "Closed"; "OTC"
Shape_Length	Perimeter of polygon	m
Shape_Area	Area of polygon	m^2

Appendix 1.8 Forest Management Database for reforestation in Fairbanks North Star Borough lands

Column names	Descriptions	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
acres	Area of harvest	acre
unit	Reforestation unit	Text
timbersale	Name of timber sale	Text
date_planted	Date of planting	MM/DD/YYYY
date_harvested	Date of harvest	MM/DD/YYYY
purchaser	Purchaser	Text
trees_planted	Number of trees planted	Numeric
reforestation_method	Reforestation method	"Plant"; "Scarification"
Shape_Length	Perimeter of polygon	m
Shape_Area	Area of polygon	m^2

Chapter 2. Early Tree Regeneration is Consistent with Sustained Yield in Low-Input Boreal Forest Management in Alaska[1]

2.1. Abstract

The boreal forest of Alaska has experienced a small area of forest cuttings, amounting to 7,137 ha out of a total of 256,284 ha of timberland in the Fairbanks and Kantishna area of state forest land. Low product values and high costs for management have resulted in a low-input type management with heavy reliance on natural regeneration. Because of increasing demand for wood biomass energy which may reduce rotation ages, understanding post-harvest regeneration is crucial. Harvested areas must meet stocking standards within seven years under the state Forest Resources & Practices Act (FRPA). We evaluated whether state forest harvest units are adequately regenerated up to 40 years following harvest based on FRPA standards in terms of stem density and biomass accumulation. We measured density of all tree size classes, and DBH and height of tree species in 726 plots from 30 representative harvest units, distributed according to harvest and treatment types, harvest year, unit size, and the geographical location of harvests. The majority of regenerated tree stems came from natural regeneration, even on planted units (77%). White spruce (*Picea glauca*) natural regeneration appears to continue for a few decades (seed crops) following harvest. Stem density was below the standard in most units surveyed during the FRPA 7-yr. period, but far exceeded the standard when resampled in this study (average 16 yrs. later), suggesting either seven years is too early to evaluate tree regeneration, or that a different standard is needed for early surveys. We found a major peak in white spruce stem

[1] Miho Morimoto, Glenn P. Juday, and Brian D. Young (2016) Early tree regeneration is consistent with sustained yield in low input boreal forest management in Alaska, Forest Ecology and Management, 373, 116.

density (45,000 ha^{-1}) in units harvested in 1987 (an historically large spruce seed crop year), suggesting that where possible, foresters need to adjust management plans according to spruce mast years. Post-harvest and post-fire successional patterns are similar, involving rapid establishment and growth of hardwoods and slow growth of white spruce, but post-harvest white spruce recruitment appears to continue longer than post-fire. By 2014 all measured harvest units met FRPA standard under low-input management, but some issues of uniformity of regeneration may remain. Although regeneration density varied among species and by management practices, biomass accumulated steadily over time (60 $t \cdot ha^{-1}$ after 40 years), largely composed of hardwoods, indicating that short-rotation forest management must utilize hardwoods. Our results are based on relatively small harvest units within a matrix of natural forest, and similar results might not occur in landscapes dominated by stands originated from more extensive and intensive management.

Keywords: low-input management, stocking standards, post-harvest regeneration, biomass, white spruce, hardwood

2.2. Introduction

Tree regeneration is an essential stage that can determine forest structure and composition for the remainder of a successional sequence, particularly for the boreal forest that is a stand replacement disturbance-driven system (Foote, 1983; Chapin *et al.*, 2006; Gauthier *et al.*, 2015). Fire is the dominant disturbance in North American boreal forest (Burton *et al.*, 2008), and numerous studies examining post-fire forest regeneration are available for Alaska and adjacent Canada (Viereck and Schandelmeier, 1980; Purdy *et al.*, 2002; Johnstone *et al.*, 2004; Johnstone and Chapin, 2006; Johnstone *et al.*, 2011; Shenoy *et al.*, 2011). However, studies of post-harvest regeneration are limited (Youngblood and Zasada, 1991; Wurtz and Zasada, 2001; Boateng *et al.*, 2009). Forest fire and forest harvest do not produce identical effects, differing in removal of coarse woody debris and the consumption of the forest organic layer (McRae *et al.*, 2001; Brassard and Chen, 2008; Ilisson and Chen, 2009), for example. Differences in successional trajectory and plant species diversity also have been detected between fire and logging disturbance (Rees and Juday, 2002; Taylor *et al.*, 2013).

The boreal forest of Alaska has experienced the smallest area or proportion of forest cuttings and regeneration management of the major forest regions of North America. Although intensive forest cutting took place locally at the time of the gold rush in the early 20th century in Interior Alaska, demand for wood declined quickly by the 1920s (Naske, 1987). The total area harvested in the Tanana Valley State Forest and forest classified lands since record collection began in the mid-20th century is about 14,000 ha (Alaska Division of Forestry, 2013b; Tanana Chiefs Conference, 2015). This harvested area compares to a total of state timberland (USDA FIA definition) of 871,000 ha in the Tanana Valley State Forest and forest classified lands (Hanson, 2013). Since Alaska statehood in 1959, local demand for wood harvest has been relatively low in Interior Alaska, and export markets have only been profitable for limited periods of high prices (Wurtz *et al.*, 2006). In the early 21st century, annual harvested volume for spruce and birch have been about 1622 and 200 mcf (1000 cubic feet), respectively from state forest lands in the Tanana Valley (Alaska Division of Forestry, 2013b), which combined is about 20 % of the estimated annual allowable cut for sustained yield (Hanson, 2013). In this situation, a form of forest management involving low-cost input with heavy reliance on natural regeneration has developed.

In Alaska, a mandate for sustainable yield was adapted within Article VIII of the State's Constitution. Elaboration of the sustainable yield mandate in the context of forestry was developed in the Alaska Forest Resources & Practices Act (FRPA)[2]. This was followed by the establishment of FRPA regulations[3]. According to these regulations, reforestation is required for all forest harvests in the State with stocking levels dependent on the exact location of the harvest. Additional regeneration efforts are required in Interior and South-central Alaska, when more than 10% of the harvest area fails to meet State regeneration standards within seven years following harvest (Table 2.1). The Alaska Division of Forestry (AKDOF) is required by the FRPA[4] to conduct regeneration surveys within seven years after harvest to ensure the stand is adequately regenerated. However, because forest regeneration in Interior Alaska may take place over an extended period of time following disturbance (Viereck and Schandelmeier, 1980), it is impractical to determine if natural regeneration has been successful based on these short term surveys. Therefore, a comprehensive, long-term investigation of tree establishment and post-harvest growth is necessary to determine whether low-cost forest management with heavy reliance on natural regeneration has met at least the first requirement for sustained yield, which is successful tree regeneration.

More recently, the demand for wood products from state land is evolving from sawlogs to woody biomass (Alaska Division of Forestry, 2013a). As of 2015, nine wood biomass energy

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[2] AS 41.17

[3] Alaska Forest Resources and Practices Regulations (11 AAC 95) implement and interpret FRPA (AS 41.17). The requirement of regeneration survey is mentioned in section 385 of the regulations. Booklets of FRPA and the regulations are available at http://forestry.alaska.gov/forestpractices.

[4]FRPA 11 AAC 95.385

facilities have been built, 10 are under construction, and more than 11 are in design or feasibility status in Interior Alaska (Alaska Energy Authority, 2015). As the new wood energy facilities begin to operate, demand for wood will increase in this region (Fresco and Chapin, 2009). The increased wood biomass energy demand will require expanded forest harvest and a change in product emphasis from large-dimension white spruce to additional species at smaller diameters. Increased birch harvest for use as firewood has already occurred (Alaska Division of Forestry, 2013b). In addition, the harvest cycle may become shorter for biomass harvest than for large-dimension wood products, requiring more frequent regeneration (Janowiak and Webster, 2010). In order to meet the needs of this evolving forest management situation on the sustained yield basis, it is crucial to understand post-harvest regeneration of all the woody species that could meet the new biomass demand.

Although the total area harvested is small, Interior Alaska boreal forest has experienced 40 years of varying harvest and regeneration practices. Forty years is too short a period to address all the issues associated with sustainable harvest through an entire rotation, but may be sufficient to address critical questions of forest regeneration. The objective of this study was to evaluate success of post-harvest regeneration up to 40 years in terms of stem density and biomass accumulation. To achieve this objective, we evaluated whether harvest units are adequately regenerated up to 40 years following timber harvest based on current stocking standards set forth in FRPA. Ours is the first broad scale study in Interior Alaska to examine, across time and space, the effects of mature forest harvest on regeneration in an operational context in which low-input management is characteristic of the region.

2.3. Methods

2.3.1. Study area

The study was conducted within the Fairbanks and Kantishna Management Areas of the Tanana Valley State Forest and forest classified lands ("state forest lands"; Figure 2.1) which covers 348,178 ha. The study area is within the Alaska boreal forest which is primarily composed of white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.)), Alaska birch (*Betula neoalaskana* Sarg.), quaking aspen (*Populus tremuloides* (Michx)), with minor amount of balsam poplar (*Populus balsamifera*), and tamarack (*Larix laricina*; Labau and van Hees, 1990). Tree cover of the state forest lands is composed of black and white spruce/hardwood forest, white spruce/hardwood forest, birch forest, white spruce forest, and white spruce/birch (Hanson, 2013). Total net cubic volume is greatest for the white spruce/hardwood and lowest for the black and white spruce/hardwood cover types (Table 2.2). Soils are mostly silt loams formed from loess parent material (Ping et al., 2006) and elevations range from 100 m to 600 m. The climate of the study area is strongly continental, but long-term climate data are primarily available for low elevation sites. Data from Fairbanks International Airport indicate a mean annual temperature of -2°C and annual precipitation of 270 mm, with extreme winter temperatures as low as -50°C. The growing season is approximately 123 frost-free days in Fairbanks since the late 20th century (Wendler and Shulski, 2009).

2.3.2. Silvicultural systems

The two primary commercial harvest methods used during the period of this study on the Fairbanks and Kantishna areas of state forest lands were clearcutting and partial cutting systems. Both of these systems were utilized for green wood and post-fire salvage harvests. The clearcut system as utilized in Interior Alaska ranged from a conventional clearcut, to a clearcut with reserves (The Society of American Foresters, 1994). Partial cuts typically involved one of two types: the removal of a single species from mixed stands, either white spruce or birch, or an intermediate harvest with diameter limits. Regardless of the harvest system, only whole tree harvesting was performed. At the time of harvest, all sampled units used in this study were dominated by the mature white spruce type which originated from fire. This study examined only units that were either clearcut or partial cut for spruce, and excludes harvest units of partial cutting for birch or post-fire salvage logging. All sampled units were harvested once between 1975 and 2004 and were not burned following the harvest.

In order to enhance seedbed quality for white spruce germination, mechanized site preparation is often applied in Interior Alaska following harvest (Youngblood and Zasada, 1991; Youngblood *et al.*, 2011). The site preparation treatments used in this study involved mechanical scarification using either a bulldozer blade or a disk trencher. We categorized units that received any site preparation as scarified regardless of the method used.

All harvest units on state forest lands relied either on natural regeneration, white spruce artificial regeneration, or small amounts of planted exotic conifers. On the Fairbanks and Kantishna areas of state forest lands the two most common artificial regeneration techniques included direct seeding or planting of container stock. For both of these methods, seeds were typically collected from local sources. In this study, we included only harvest units that experienced natural regeneration or planting of white spruce seedlings from container stock.

Historical harvest units on the Fairbanks and Kantishna areas of state forest lands varied in size from ~ 1 to a few hundred ha (Figure 2.2a). The size distribution of the harvest units was positively skewed, with a median of 4.66 ha and a mean of 10.89 ha. We excluded the smallest units (< 1 ha) and extremely large units (> 40 ha). The harvest units included in this study ranged from 1.4 – 30.3 ha in size (Figure 2.2b). The total area of sampled harvest units is 269 ha, which is about 3.5% of total harvested area (about 7,000 ha) on the Fairbanks and Kantishna areas of state forest lands.

2.3.3. Sampling layout

We chose 30 harvest units on the Fairbanks and Kantishna areas of state forest lands from the Alaska Division of Forestry (AKDOF) Forest Management Database (Alaska Division of Forestry, 2013b). The AKDOF Forest Management Database is a GIS-based database collection of records of the location and type of all management activity that has occurred on state forest lands within the Fairbanks and Kantishna areas since 1972 archived in Microsoft Access (see Figure 2.1; Alaska Division of Forestry, 2013b). Using this database, we selected representative harvest units that were evenly distributed according to harvest and treatment types, the year of timber sale, size of harvest units, and the geographical location across the study area (Table 2.3). Sampled harvest units are located in both upland and floodplain sites. To compare our results to operational regeneration surveys conducted within 7 years following a harvest, we used the same plot size for sampling as AKDOF surveys, 1.69 m radius circular plots (Alaska Division of Forestry, 2008). We chose sampling intensity of four plots ha^{-1}, which was generally lower than the AKDOF surveys' 12.4 to under 3 plots ha^{-1} depending on the size of the harvest unit (Alaska Division of Forestry, 2008). However, a preliminary test of sampling efficiency of the selected number of plots ha^{-1} using a censused population of white spruce in the study region demonstrated that it was adequate to obtain valid tree density data (Juday, 2012). To determine the placement of plots, we created a virtual 50 m × 50 m grid with points at the center of each cell over the entire study area using the fishnet tool in ArcGIS version 10.2 (ESRI, 2013; Figure 2.3). ArcGIS points falling within the selected harvest units represented the center of the plots. The number of plots in each unit varied between 7 and 120 due to the size and geographic configuration of the harvest units (Table 2.3). Because we prioritized sampling a large number of harvest units over intensive sampling in a single harvest unit, the sampling intensity was truncated in larger units. When the standard of four plots ha^{-1} totaled more than 50 plots, we sampled only every other plot, or every third plot when the unit was larger than 100 plots at the four plots ha^{-1} standard. In units where only every other or every third plot was sampled, plots were selected to evenly distribute them starting from the first plot (Figure 2.3). The coordinates of the plots (+/- 1m) were exported to a Trimble Pro XT GPS unit (Trimble Navigation, California) and were used to navigate to the sample plot centers.

2.3.4. Data collection

Field sampling was conducted during the summer of 2013 and 2014. Within each plot, we counted and recorded all tree species presented in the plots including, white spruce, birch, aspen, balsam poplar, and black spruce. All woody stems in each plot were counted by size class and origin. Stems were categorized into small (< 2.5 cm DBH) and large (≥ 2.5 cm DBH). When a live white spruce was 30 cm or taller, we measured total height and basal diameter, unless the tree was ≥ 1.37 m in height in which case we measured height and DBH. For live birch, aspen, balsam poplar, and black spruce > 1cm DBH, we measured DBH and height. The origin of all stems was classified into, a) natural regeneration, b) planted (only for white spruce), or c) residual stems from pre-harvest. Planted white spruce seedlings were distinguished from seedlings of natural origin based on age, growth pattern in early age, and alignment in planted rows with other white spruce stems when visible. Residual stems were distinguished from regeneration based on estimated age of the tree. In this study, we considered only actual regeneration following harvest. The sampling protocol for this study will be made available at Bonanza Creek Long Term Ecological Research Site website (http://www.lter.uaf.edu/).

We also used data of regeneration within 7 years post-harvest collected by AKDOF operational surveys (early surveys). Early surveys were available for 13 of our harvest units. The data are available in the AKDOF Forest Management Database (Alaska Division of Forestry, 2013b).

2.3.5. Evaluation of regeneration success

The regeneration stocking standard currently in place within the Alaska state forest for sustainable management is based on the minimum tree stem density that must be present within seven years following harvest. Tree stems that count toward meeting the stocking standard are weighted by size classes, with fewer larger stems required and greater numbers of small stems required (Table 2.1). For purposes of meeting the requirements of FRPA regulations, a 1.69 m radius circular plot is evaluated as meeting the stocking standard if it contains a sufficient number of stems, when expanded to per hectare values, to equal or exceed 100% of the minimum stem density. The minimum stem density can be met by stems from any of the size classes, or a sufficient weighted combination of stems from all of the size classes (Table 2.1).

In this study, we calculated the percent stocking standard achieved on each plot, and the percent of plots that met or exceeded the standard (Alaska Division of Forestry, 2008). Percent stocking standard achieved on each harvest unit as a whole was calculated as the mean of plot percentages (Alaska Division of Forestry, 2008). We were also interested in determining whether harvested units met the standard without planted seedlings, so we calculated the percent stocking standard contributed by naturally regenerated trees separately.

We calculated the proportion of plots meeting the standard in each unit, both for combined natural and planted regeneration, and for natural regeneration alone. In order to examine the effects of year since harvest on achievement of the stocking standard, we divided the harvest units into young (logged up to 20 years ago or post-1994) and old (logged 21-40 years ago or pre-1994) harvest units. Pre-1994 harvest units include 416 plots from 19 units. Sampled post-1994 harvest units include 310 plots from 11 units. We calculated the difference between the proportion of plots meeting the standard through the combination of natural and planted regeneration versus natural regeneration alone both for pre-1994 and post-1994 harvest units, and tested for significance of difference using a t-test in R (R Core Team, 2014). We used significance level of $\alpha = 0.05$.

We compared the stem density obtained from AKDOF operational regeneration surveys (early surveys) conducted within 7 years after harvest (one unit was surveyed after 10 years) with our results (2013 survey) in 13 harvest units. We could not directly calculate percent stocking standard from the early regeneration surveys because tree size was not recorded in those surveys. However, because operational surveys were conducted in earlier stages of regeneration, we assumed that the stems would be in the smallest size class (Table 2.1). We compared our results with the early survey by assuming that if units did not contain 1,112 seedlings per hectare or greater at the time of the early surveys, they had not achieved the stocking standard.

We evaluated biomass accumulation up to 40 years following harvest. For biomass calculation, we used biomass equations established using samples from Interior Alaska (Yarie *et al.*, 2007). The equations follow the form:

$$Y = \alpha_1\text{*DBH} + \alpha_2\text{*DBH}^2 + \alpha_3\text{*height} \qquad \text{(Equation 2.1)}$$

where Y is the total above ground biomass (grams), and α_1, α_2, and α_3 are specific coefficients for each species (for more details refer to Yarie *et al.*, 2007).

2.4. Results

2.4.1. Stocking density

White spruce and Alaska birch are the most abundant regenerating (non-residual) tree species (Figure 2.4ab). Apart from a peak in units harvested in 1987-88, stem density appears to generally decrease with time since harvest (Figure 2.4a). White spruce contributes disproportionately to the 1987-88 peak in density of stems of all sizes (Figure 2.4a). However, the 1987-88 peak in large regenerating stems is composed primarily of birch (Figure 2.4b). As expected, the younger units supported high absolute densities of regenerating birch and aspen. When considering stems of all sizes, the proportion of white spruce in older units was higher than in the younger units (Figure 2.4a). However, for large stems, the proportion of white spruce in younger vs. older units did not increase to the same degree (Figure 2.4b).

Overall, 53% of the units were planted and 47% were solely naturally regenerated. Proportions of planted vs. naturally regenerated units in the first half vs. second half of the period of analysis are roughly similar (Table 2.3). Even when planted seedlings are excluded, all units met or exceeded the established numerical goal of the state's stocking density standard when considered as a whole (Tables 2.1 and 2.4). The contribution of planted white spruce seedlings toward the stocking standard decreased through time. The difference in percent stocking standard contributed by combined natural and planted seedlings compared to natural seedlings alone was lower in the older harvested units than the younger units, demonstrating that planted seedlings were less important in older units (Table 2.4; *pre-1994 difference,* mean = 2.4%; *post-1994 difference,* mean = 6.0%; $t = -2.60$, $p = 0.010$).

All units had a considerably (about 14-fold) greater stem density in our study (2013/14) than in the early operational regeneration survey conducted by AKDOF (Figure 2.5ab). Although 6 out of 13 units did not meet the stocking standard in the early survey, in our study all the units exceeded the standard (Figure 2.5a). Density of larger stems in our 2013/14 study was about 50% greater than density of stems of any size in the early surveys (Figure 2.5b).

Although all units met or exceeded the standard as a whole, not all the plots within units met the standard (Table 2.4). Overall, 87.5% of the plots met or exceeded the standard when natural and planted regeneration were combined, and 81.8% with natural regeneration alone. The proportion of plots meeting the standard was substantially greater in our 2013/14 study than in the early survey (2013/14 = 90.4 ± 4.2% (mean ± 1 SE); early survey = 46.1 ± 5.5%). In the early survey, the proportion of plots meeting the standard through the combination of natural and planted regeneration was much higher than through natural regeneration alone (difference = 26.6 ± 6.0 %). In contrast, in our 2013/14 study, the proportion meeting the stocking standard by the combination of natural and planted seedlings was almost the same as the proportion meeting the standard by natural regeneration alone (difference = 3.7 ± 3.7 %).

2.4.2. Accumulation of biomass in harvested units

The amount of biomass accumulated in the harvest units was variable, with biomass accumulation below 5 $t \cdot ha^{-1}$ in the youngest units and a peak value of about 95 $t \cdot ha^{-1}$ in the older units (Figure 2.6). Despite the variability, biomass accumulation was smaller in the younger units than in older units in general (Figure 2.6). Birch and white spruce, with aspen in some years, constitute a great portion of biomass accumulation (Figure 2.6). Birch was the most abundant regenerating tree species in terms of total biomass for the entire study period, except for units harvested in 1983-84 (total biomass accumulation: birch = 63%, white spruce = 18%, and aspen = 13%).

2.4.3. Tree diameters

Maximum DBH of white spruce was greatest in the units harvested about 25 years earlier (1987-88 harvests), but was not markedly different in units harvested in the decade before compared to after (Figure 2.7a). After the earliest phase of regeneration (up to 15 years), mean and maximum DBH of white spruce fluctuate by year of harvest (Figure 2.7a). No plots contained white spruce saplings (>2.5 cm) until about 15 years after harvest. After 1987 the proportion of plots with sapling white spruce was about the same among year of harvest, except for a peak in stands harvested in 1987-88.

For the first 25 years following harvest, birch mean and maximum DBH, and the proportion of plots containing birch saplings showed an increasing trend (Figure 2.7b). After that, birch mean and maximum DBH, and the proportion of plots containing birch saplings did not show a clear trend and varied greatly by years (Figure 2.7b). Mean DBH in units 40 years after harvest was about 3 cm (Figure 2.7b). Overall, birch DBH was greater than white spruce DBH (Figure 2.7ab).

2.5. Discussion

Sustainability is a vague but widely accepted concept in forest management, and regeneration following disturbance plays an essential role in sustainable forest yield, particularly for stand replacement disturbance-driven system such as the boreal forest (Rowe and Scotter, 1973; Foote, 1983; Chapin *et al.*, 2006; Gauthier *et al.*, 2015). However, until this study, the Alaska FRPA regulations stocking standards (Table 2.1) have not been empirically tested either for achievability or for their contribution to sustainability. As a result, the lessons of 40 years of operational tree regeneration experience reported here can serve as a principal point of reference for assessing the relevance of FRPA regulations to sustainability.

The success of all our study harvest units in meeting the State stocking density standard is notable (Tables 2.1 and 2.4), particularly given the heavy reliance on natural regeneration. However, an average of about 20% of our plots within harvest units did not meet the standard, indicating that some issues of heterogeneity of regeneration may remain. Planting might be desirable in those areas with low natural regeneration. In younger units (< 20 years), planted seedlings appear important in supplementing natural regeneration to meet the standard, while in older units (> 20 years), natural regeneration alone was sufficient to meet the standard (Table 2.4). Unlike early successional hardwood species, such as birch and aspen, which establish most seedlings or asexually reproducing stems in the earliest phase of regeneration, white spruce recruitment may continue for a more extended time after disturbance, mostly with sporadic mast events (Rossi *et al.*, 2012). In our study area, white spruce natural regeneration appeared to continue to fill up (or expand within) unregenerated areas in harvest units at least until 40 years post-harvest (Figure 2.4). Our results may include a small amount of bias against the recognition of planted white spruce seedlings. It was harder to distinguish planted from naturally regenerated white spruce in units that were logged in earlier years compared to units harvested more recently. However, planting was not widely used in the early period of analysis.

Early regeneration surveys conducted by AKDOF ($\leq$ 7 years after harvest) found that about half of our sampled units did not meet the State stocking standard (Figure 2.5). However, apparent stem density, and obviously the density of larger stems, increased substantially between the early survey and the time of our sampling (Figure 2.5). All units exceeded the standard in 2013/14, which was ten years or more following harvest (Figure 2.5). There are two likely explanations for this increase in stem density. First, herb and grass cover may have dominated the site immediately after harvest to such a degree that the time required for tree regeneration was prolonged. Such herb and grass dominance in our study region is well-known in the initial stage of regeneration following disturbance (Rydgren *et al.*, 2004; Chapin *et al.*, 2006). This suggests that either seven years after harvest might be too early to evaluate tree regeneration as a contributor to sustainable yield, or that a different standard is needed for early surveys. The second likely explanation for the increase in stem density involves the different sampling protocols used in the two evaluations. Stem density was most likely underestimated in AKDOF surveys due to the quick, and sometimes simplified stem counting by using category, such as "10-20 stems". By contrast, our protocol involved a careful search for and a count of all tree stems present. However, particularly because of the magnitude of the difference in stem density between the two evaluations, we believe that stem density did actually increase over time, and that this mostly accounts for the increase in units meeting the standard.

Sustainable forest management in North American boreal forest is often evaluated by comparing the consequence of management to that of wildfire (Attiwill, 1994; Bergeron *et al.*, 2002). We found that post-harvest natural regeneration, in general, follows a similar successional pattern to that seen following high severity fire, but white spruce recruitment following harvest may take place for a longer time. Regeneration following high severity fire is dominated by deciduous trees in a great majority of cases (Bergeron, 2000; Chen *et al.*, 2009; Johnstone *et al.*, 2010). Most white spruce recruitment is limited to a few years after fire, because seedbed quality declines rapidly as post-fire succession advances (Purdy *et al.*, 2002). However, post-fire white spruce recruitment could occur after the initial recruitment phase if there is a suitable substrate for spruce germination, such as partially decomposed logs (Peters *et al.*, 2006). Over time, white spruce established early in the process of stand development become a more prominent part of the stand, especially those trees that find a favorable canopy position (Youngblood, 1995; Chapin *et al.*, 2006). Generally, hardwood species have advantages in the early phase of post-fire regeneration over white spruce for several reasons. Although white spruce regenerate only from seed (Nienstaedt and Zasada, 1990), birch and aspen regenerate both sexually and asexually (Perala, 1990; Safford *et al.*, 1990). Birch and aspen vigorously sprout from stumps and roots, respectively, when mature trees are cut (Perala, 1990; Safford *et al.*, 1990). As a result, regeneration of birch and aspen is denser and more vigorous than white spruce from the earliest life of the stand. In addition, most white spruce seed falls within 100-150 m from the seed source (Youngblood and Max, 1992), so the species is frequently limited by seed dispersal distance. Competition with hardwoods and early-successional vegetation is also an issue for white spruce early growth, because of its generally slower rate of early growth (Youngblood and Zasada, 1991; Youngblood and Max, 1992; Youngblood, 2012). Therefore, post-fire regeneration usually begins with dense hardwood regeneration, followed by a rapid decline in stem density due to competition. White spruce with poor canopy position grow slowly and, if they can persist, require several decades to a century to enter the canopy (Chapin *et al.*, 2006).

These same limitations and patterns are present in our post-harvest units. Birch dominated in the early phase of regeneration, but the overall birch density was lower in older compared to younger units, apparently due to self-thinning, while stems that survived the competition grew larger (Figure 2.4ab). The same patterns to a lesser degree occurred in aspen (Figure 2.4ab). White spruce recruitment appears to continue for a few decades (Figure 2.4ab). The overall density of white spruce was relatively low in units at the early phase of regeneration and increased gradually in older units up to the 40-year maximum in our study (Figure 2.4a). Although the overall density of white spruce was similar to the density of other tree species at 40 years following harvest, smaller numbers of spruce saplings (> 2.5 cm DBH) were present compared to hardwood species in the oldest units due to slower rate of spruce growth, particularly compared to birch (Figure 2.4).

White spruce regeneration density is also affected greatly by sporadic seed production (Juday *et al.*, 2003; Roland *et al.*, 2014). White spruce is a masting (Kelly, 1994) species and produces large seed crops only about every 10 years in boreal Alaska (Juday *et al.*, 2003; Roland *et al.*, 2014). We observed a major peak in established stem density in units harvested in the 1987-88 time period, which was an historically large white spruce seed crop year (Juday *et al.*, 2003; Roland *et al.*, 2014). White spruce contributed substantially to the apparent 1987-88 density peak, when considering all trees (Figure 2.4a), as well as saplings (> 2.5 cm DBH; Figure 2.4b). Despite the high competition among trees due to the high density, birch regeneration appeared to be successful in this time period as birch sapling density in units harvested in that time period was the highest observed (Figure 2.4b). Two possible explanations may have contributed to this result. First, the high density of both white spruce and birch might have been the result of particularly favorable environmental conditions and/or a favorable growth period in those years. Alternatively, only one sampled unit was harvested during 1987-88 (unit NC-305) suggesting that lack of sample depth may have influenced the result. However, we believe the 1987-88 result is real. Other mast years occurred during the period of analysis, but none produced an equivalent amount of white spruce recruitment in the harvest units. The 1987 white spruce seed crop is unsurpassed during the period of analysis in terms of the combination of volume of seeds and seed viability across a broad area of Alaska (Roland *et al.*, 2014). The density peak of white spruce in units harvested in the mid-1980s (Figure 2.4a) represents strong evidence that units harvested in the mid-1980s provided suitable seedbeds for the exceptional 1987 seed crop.

Other years that are reported to have either moderate to high seed fall and/or high seed viability between 1975-2004 include 1983, 1990, 1997-98, and 2000 (Zasada, 1985; Roland *et al.*, 2014). A modest recruitment peak does appear to be present in units harvested in the early and late 1990s (Figure 2.4ab), which would correspond to the 1997-98 modest seed crops and seedbed availability. Determining the influence of smaller white spruce seed crops is more challenging than for exceptional seed crops because abundant seedling establishment is generally associated only with a major mast year that exceeds a threshold amount of seed fall (Rossi *et al.*, 2012). Nevertheless, foresters need to keep in mind the influence of periodic white spruce seed crops as they plan future harvests, and where possible adjust management plans according to actual or anticipated white spruce mast years. This might include reducing seedbed preparation in mast years to avoid overstocking or applying site preparation to enhance seedbed quality in years with no/low white spruce seed crop.

As expected, biomass accumulated steadily over time, and the total accumulation was between 40-100 $t \cdot ha^{-1}$ after a little less than 40 years post-harvest. Although the change of regeneration density varied among species and site or management variables, apparently regeneration success did not change markedly through the period of analysis nor did mortality of newly established trees. Biomass accumulation overall was largely composed of hardwoods, including birch, aspen, and balsam poplar (Figure 2.6). As a result, it seems obvious that a short-rotation forest management system in this part of the boreal forest must be prepared to utilize primarily woody materials from hardwood species, unless strenuous efforts are made to establish white spruce. Where forest management goals can be met largely by hardwood material, the management regime applied in our study area would be successful.

White spruce DBH and the proportion of plots that contain white spruce saplings appeared to increase only for the first 15 years after harvest, and growth might slow down substantially after that time period (Figure 2.7a). White spruce that fail to achieve unobstructed canopy position grow slowly under hardwoods for decades, until the hardwood component starts declining (Chapin *et al.*, 2006). It appears that white spruce diameter growth in the early phase of regeneration is not necessarily associated with time since harvest but may be more influenced by variability in environmental conditions, especially the degree of hardwood competition, among units. The historical seed crop in 1987 not only increased stem density of white spruce but also associated with a period of favorable growth (Figure 2.7a). Birch DBH increased more steadily in older harvest units compared to white spruce (Figure 2.7ab). As some stems grow larger, mortality of the other, suppressed stems increases. As a result, the proportion of plots that contain birch saplings can vary by year of harvest (Figure 2.7b) due to the degree of local competition and dominance. Birch DBH and the proportion of plots that contain birch saplings was very small in 1983-84 period (Figure 2.7b), while white spruce regeneration during those years was as successful as units harvested in other time periods. This suggests that weather was not poor then for tree growth in general. Instead, it may be that birch experienced low seed production during this time period, and was outcompeted by white spruce during the early phase of regeneration. We have only one harvest unit sampled in this time period, and thus further investigation could help determine whether birch regeneration was actually less successful during this time period. In any event, birch generally grows faster than white spruce (Figure 2.7ab; Safford *et al.*, 1990), suggesting that birch would be a more suitable species for short-rotation biomass harvest if the products were equally usable.

The thirty harvest units in this study, evaluated 10-40 years following harvest and distributed across an area of 8,400 km^2, all met State stocking density standards at the time of our evaluation despite the heavy reliance on natural regeneration. All the harvest units analyzed in this study were originally mature stands dominated by white spruce and, to date, have regenerated into mixed forest, suggesting that sustaining white spruce would take longer than sustaining total wood biomass. It is important to note that we analyzed a set of relatively small harvest units within a matrix of natural forest, and similar results might not occur once the area of stands originated from management became a greater portion of the total landscape. For example, white spruce might gradually decrease in managed forests if a short-rotation, hardwood focused management with a heavy reliance on natural regeneration becomes the major type of management. A number of issues relating to sustainability also remain, even with a better assessment of regeneration than has been available before.

The history of 40 years of forest development in harvest units still represents only one-half to one-third of rotation age assumed when these stands were initiated (Hanson, 2013). Looking forward, issues of the risks of tree and stand mortality will play an increasingly important role in the questions of long-term succession. Moreover, there are other important factors that need to be considered when thinking about sustainable forest management, such as biodiversity and provision of wildlife habitats. Forest harvest can supplement natural disturbance to create diverse landscape patterns and valuable habitats for wildlife if it is applied skillfully. It is apparent that further research is necessary to understand and implement sustainable management, but we believe the results of this study provide a useful starting point. Considering all of our findings, it appears desirable to evaluate whether the State stocking standard is effective in assessing post-harvest regeneration, particularly within the seven year time frame. Partly as a result of this study, a formal FRPA Science and Technical committee review process of reforestation was launched. In particular, more systematic and frequent post-harvest surveys will be required to remain confident of sustainable yield.

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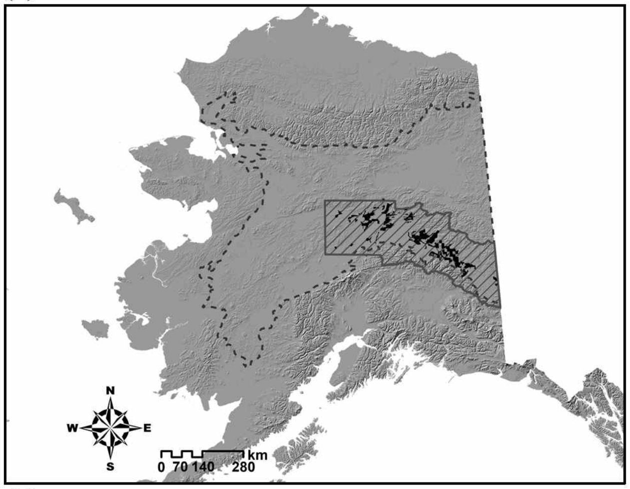
2.8. Figures

(a)



(b)

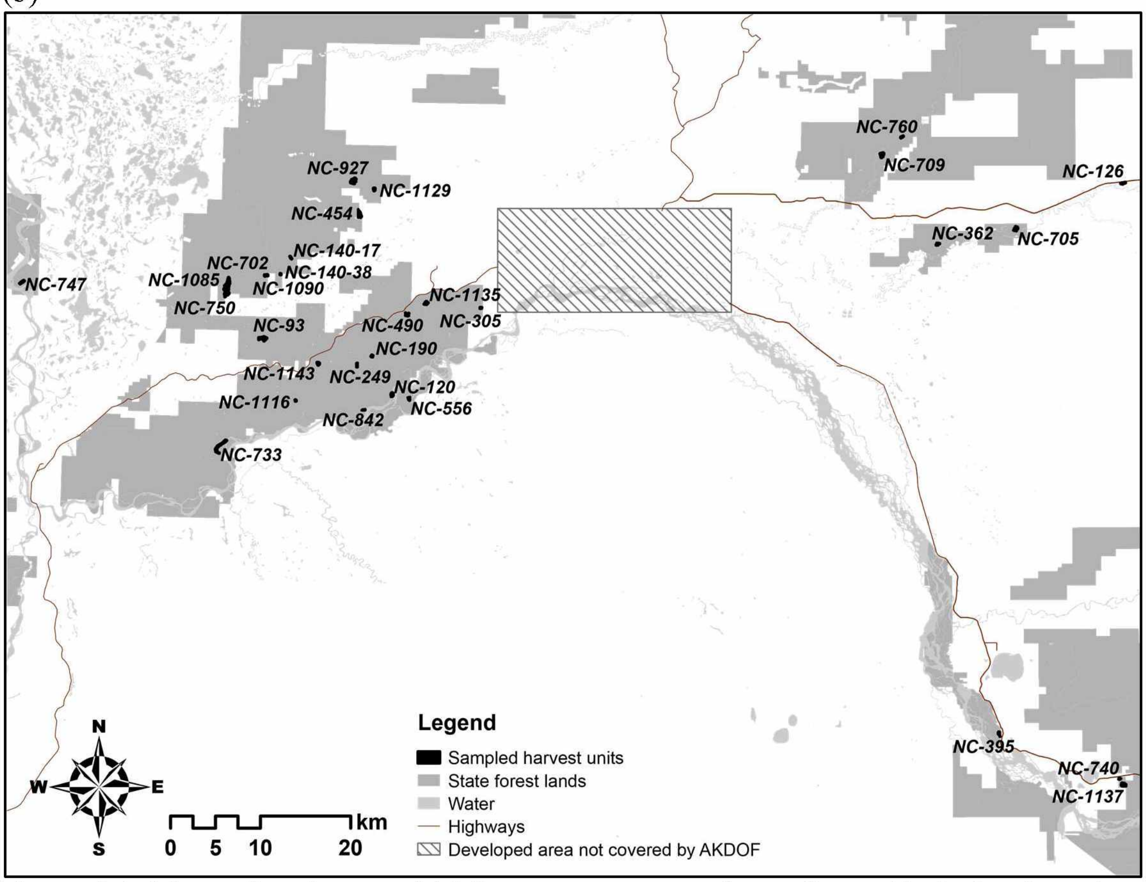


Figure 2.1. Maps of study area. (a) Management areas of state forest (dashed polygon) and the Tanana Valley State Forest and forest classified lands (black polygons; 1,162,000 ha) within the Tanana Valley which is drained by the large silt-bearing Tanana River in Interior Alaska boreal region (dashed boundary; Hanson, 2013). (b) Fairbanks and Kantishna areas of Tanana Valley State Forest and forest classified lands. NC- followed by number represents the ID label of a sampled harvest unit.

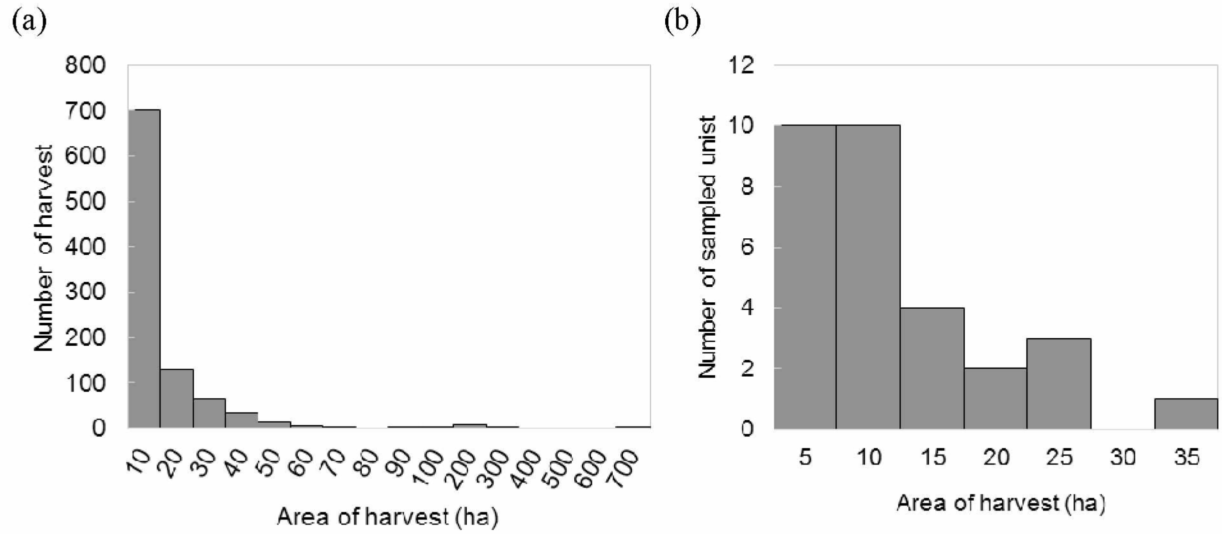


Figure 2.2 Histogram of harvest size of (a) historical harvest units, and (b) sample units in the Fairbanks and Kantishna areas of Tanana Valley State Forest and forest classified land.

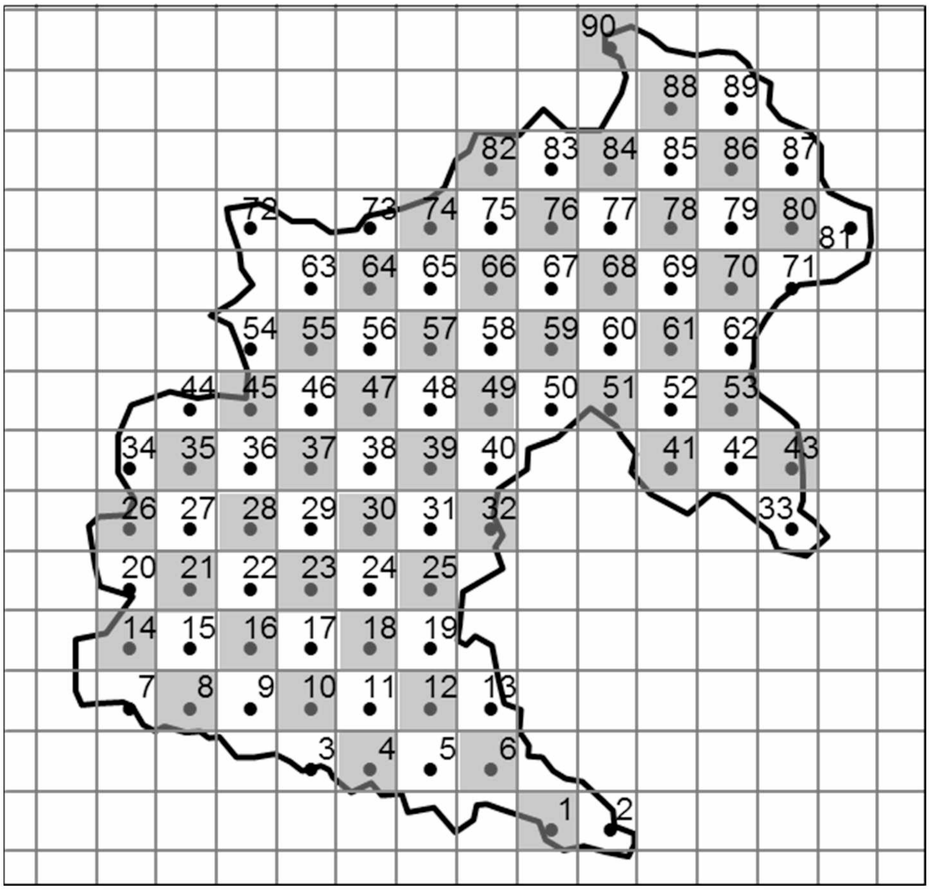


Figure 2.3. Example of plot placement and selection. The size of the grid is 50 m. Dots represent plots and the numbers above them represent plot labels. In units with more than 50 plots, every other plot was selected (shaded cells).

(a)

(b)

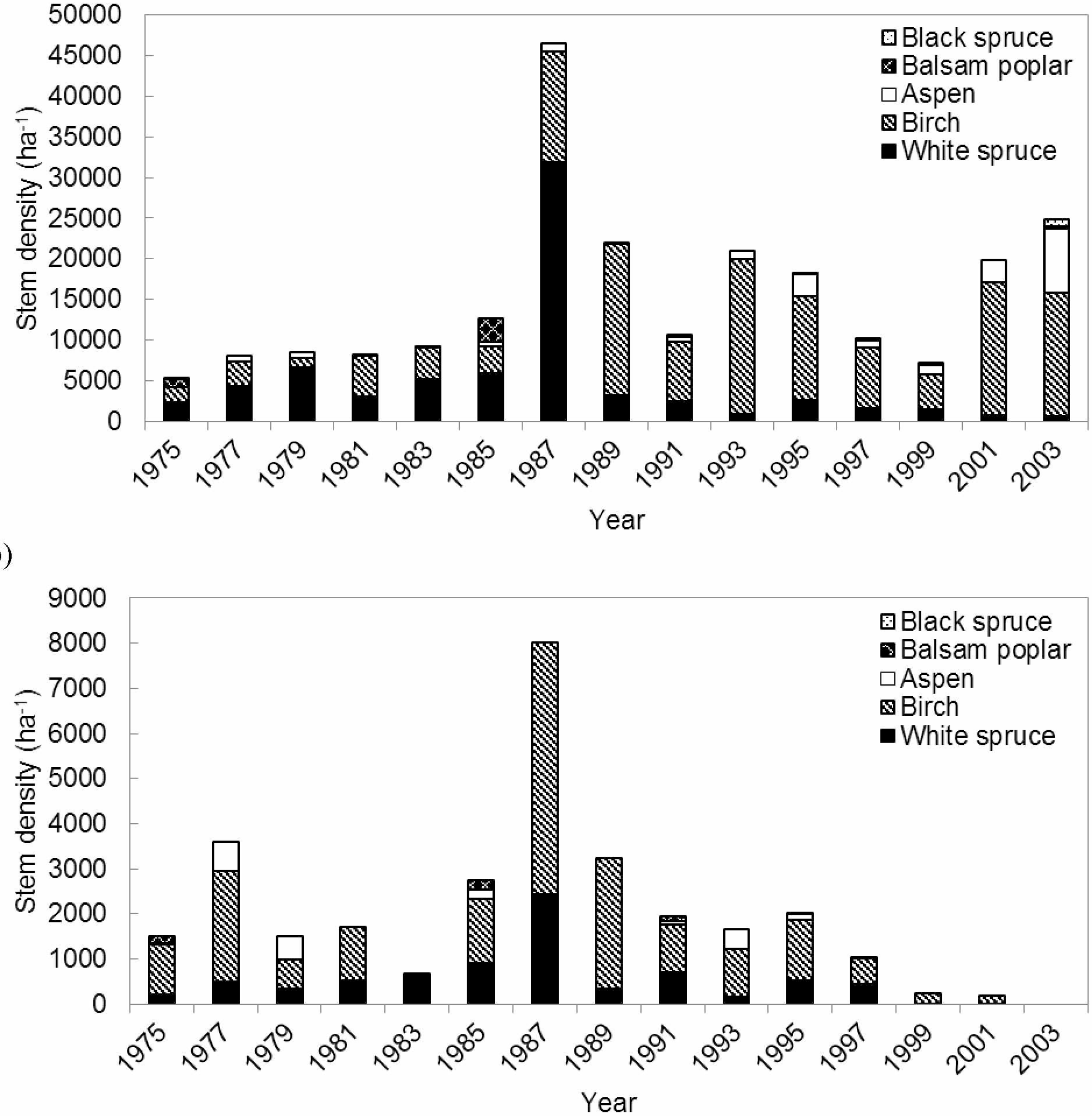
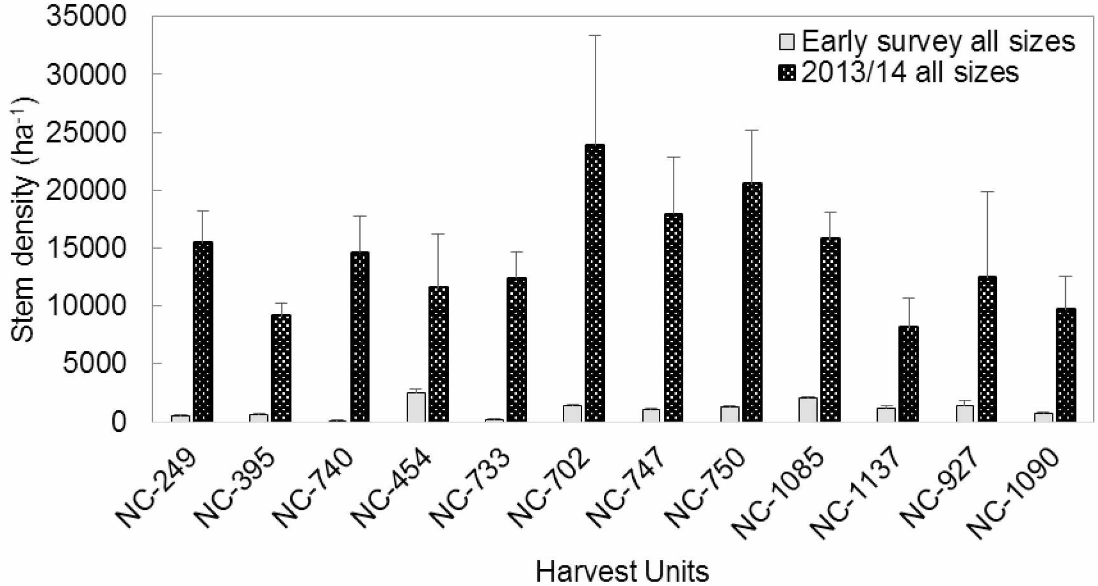


Figure 2.4. Stem density (ha^{-1}) by two-year classes of period of harvest (beginning year) by species for (a) all diameters and (b) large stems (DBH ≥ 2.5 cm).

(a)



(b)

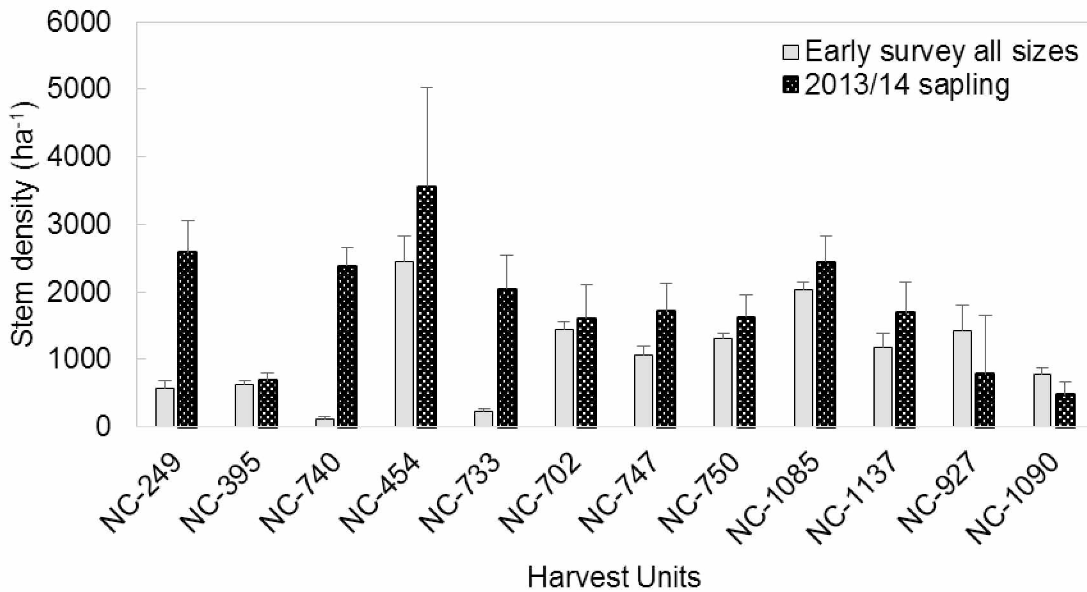


Figure 2.5. Comparison of stem density of (a) all sizes between early survey conducted by AKDOF within 7 years of harvest and our 2013/14 study and (b) all sizes in early survey to stems ≥ 2.5 cm in our 2013/14 study. Error bars represent 1SEs.

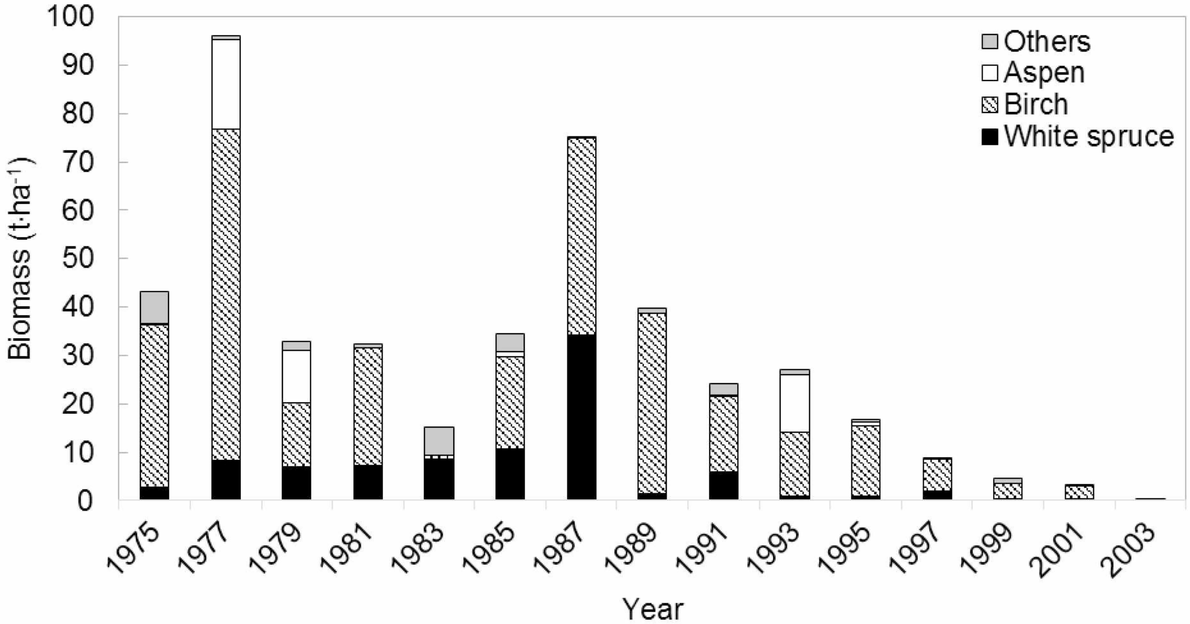
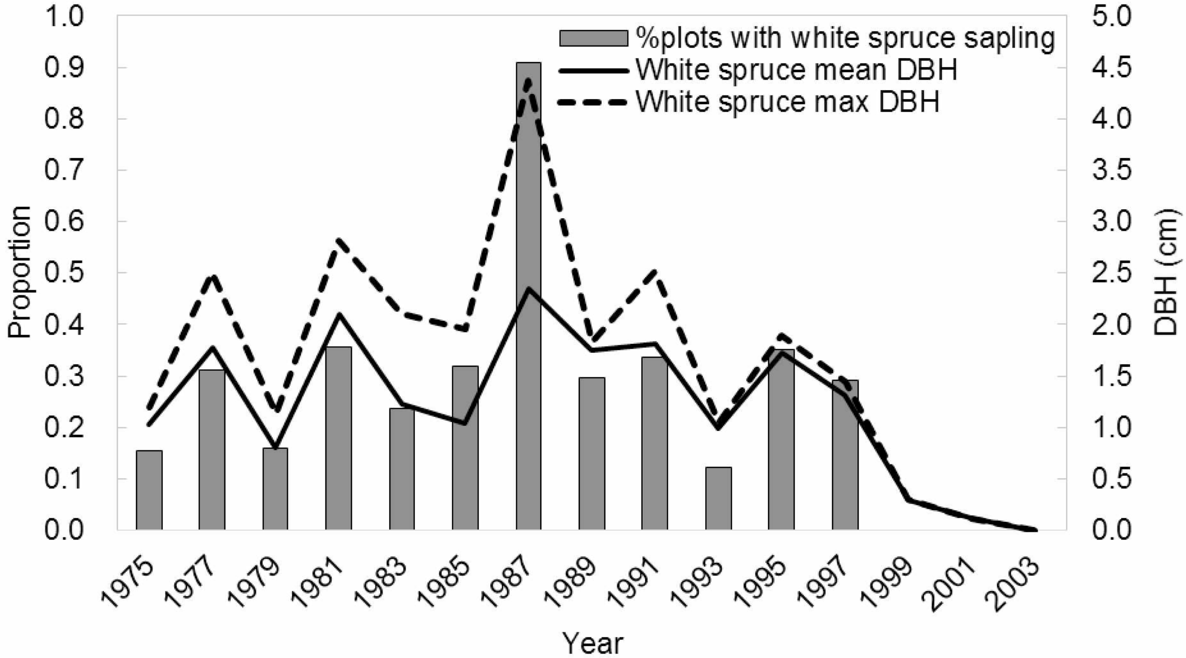


Figure 2.6. Biomass of regenerated stems post-harvest by two-year classes of period of harvest (beginning year)

(a)



(b)

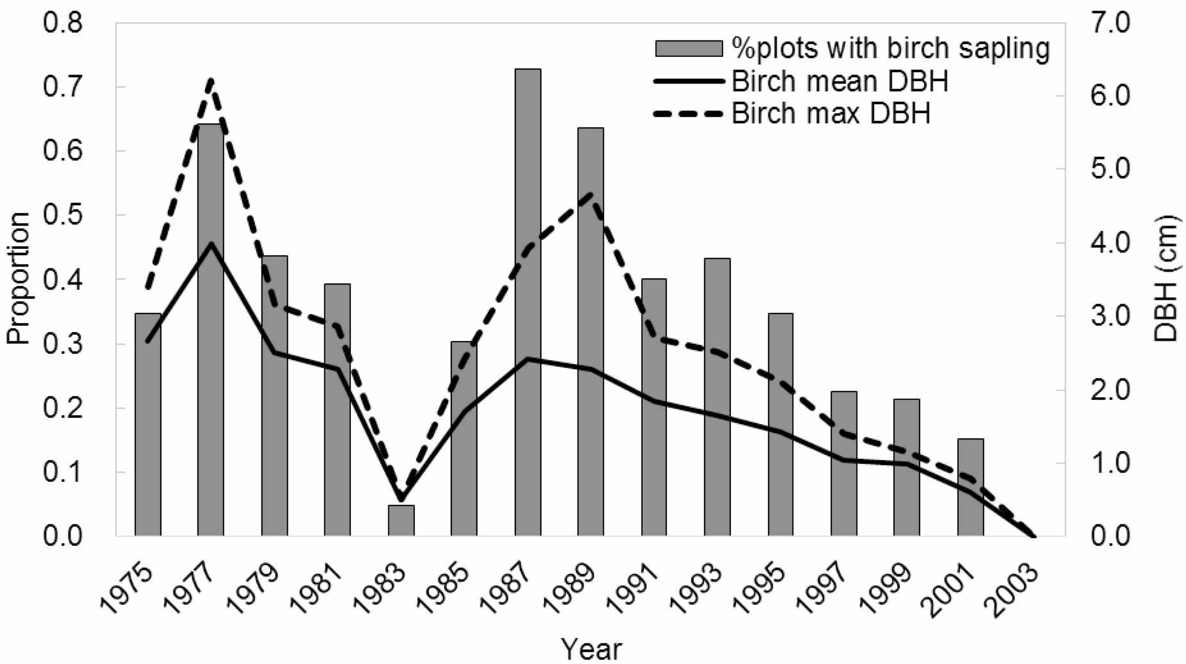


Figure 2.7 Proportion of plots that contain saplings, and mean and maximum DBH by two-year classes of period of harvest (beginning year) of (a) white spruce, and (b) birch.

2.9. Tables

Table 2.1 Post-harvest stocking standard established by the State of Alaska.

DBH (cm)	Minimum Stocking Standard (trees ha^{-1})
Seedlings	1,112
2.5-15.2	495
15.2-22.9	420
>22.9	297

Note: Example of calculation of percent stocking for seedlings

$$\% \text{ stocking} = (d/1112) \times 100$$

where d is the stem density ha^{-1} measured in each plot. Percent stocking standard was calculated similarly for the other three size classes for their minimum density values.

Table 2.2 Tree cover of the Tanana Valley State Forest. MCF = 1000 cubic feet, and MBF = 1000 board feet (Hanson, 2013).

			Total Net Volume		
Vegetation Type Class	Area (ha)	% of area	Cubic Foot (MCF)	Cubic Meter (m^3)	Board Foot (MBF)
Aspen	32,682	4	169,723	4,806	178,742
Birch	88,299	10	354,235	10,031	407,868
Black and White Spruce/Hardwood	314,153	36	206,781	5,855	188,124
Hardwood	35,758	4	151,681	4,295	235,158
White Spruce	67,679	8	419,564	11,881	1,344,723
White Spruce/Balsam poplar	11,033	1	45,692	1,294	88,061
White Spruce/Birch	58,530	7	245,802	6,960	761,953
White Spruce/Hardwood	263,128	30	479,282	13,572	852,877

Table 2.3. List of sampled harvest units

Unit	Size (ha)	# plots (calculated)	# plots (sampled)	Logged year	Harvest type	Site preparation	Reforestation
NC-120	10.4	41	41	1975	Partial cut	None	Plant
NC-93	17.9	76	35	1975	Partial cut	None	Natural
NC-190	5.1	22	22	1977	Clearcut	Scarify	Natural
NC-126	5.7	22	22	1978	Partial cut	None	Natural
NC-140-17	2.5	8	8	1979	Clearcut	None	Natural
NC-249	5.0	22	22	1980	Clearcut	Scarify	Natural
NC-362	4.4	15	15	1981	Partial cut	None	Natural
NC-140-38	1.5	7	7	1982	Clearcut	Scarify	Natural
NC-395	5.1	21	21	1983	Clearcut	None	Natural
NC-490	8.4	32	32	1985	Clearcut	None	Natural
NC-556	6.6	26	26	1986	Clearcut	None	Plant
NC-305	3.5	11	11	1987	Partial cut	Scarify	Plant
NC-705	11.0	44	44	1989	Clearcut	Scarify	Plant
NC-454	20.4	87	44	1991	Clearcut	Scarify	Plant
NC-740	1.9	8	8	1991	Clearcut	None	Plant
NC-709	17.2	71	35	1991	Clearcut	Scarify	Plant
NC-842	2.1	7	7	1992	Partial cut	None	Natural
NC-733	30.3	120	44	1992	Clearcut	Scarify	Plant
NC-702	2.0	9	9	1993	Clearcut	None	Plant
NC-747	8.0	31	31	1994	Clearcut	None	Plant
NC-750	9.8	41	41	1995	Clearcut	Scarify	Plant
NC-1085	22.6	94	47	1996	Partial cut	Scarify	Plant
NC-1137	13.5	55	29	1997	Clearcut	None	Plant
NC-927	22.5	90	43	1998	Partial cut	None	Plant
NC-760	3.4	13	13	1998	Partial cut	None	Natural
NC-1129	6.0	22	22	1999	Partial cut	None	Plant
NC-1090	1.4	7	7	1999	Partial cut	None	Natural
NC-1135	11.7	49	49	2002	Partial cut	None	Plant
NC-1116	2.4	9	9	2003	Partial cut	Scarify	Natural
NC-1143	6.7	28	28	2004	Partial cut	None	Natural

Table 2.4 Percent stocking standard and percentage of plots meeting the standard. Natural = natural regeneration

Units	Year of harvest	Density ha^{-1}		% plots stocked		
		Natural & Planted	Natural	Natural & Planted	Natural	Diff.
NC-93	1975	5824	5824	-	90%	-
NC-120	1975	4622	4556	56%	56%	0%
NC-190	1977	9726	9726	-	95%	-
NC-126	1978	6396	6396	-	87%	-
NC-140-17	1979	1393	1393	-	75%	-
NC-249	1980	15451	15451	-	86%	-
NC-362	1981	10428	10428	-	71%	-
NC-140-38	1982	5732	5732	-	86%	-
NC-395	1983	9181	9181	-	86%	-
NC-490	1985	9632	9632	-	82%	-
NC-556	1986	15770	15770	85%	85%	0%
NC-305	1987	46505	44174	100%	100%	0%
NC-705	1989	21809	21530	82%	82%	0%
NC-740	1991	14648	14329	100%	100%	0%
NC-709	1991	8981	8457	76%	74%	3%
NC-454	1992	11580	10846	93%	90%	2%
NC-733	1992	12445	11543	98%	93%	5%
NC-842	1992	4140	4140	-	71%	-
NC-702	1993	23900	23652	89%	78%	11%
NC-747	1994	17943	17943	90%	90%	0%
NC-750	1995	20573	20452	81%	76%	5%
NC-1085	1996	15793	15295	94%	89%	4%
NC-1137	1997	8147	7417	100%	86%	14%
NC-760	1998	11753	11753	-	64%	-
NC-927	1998	12482	11758	98%	95%	3%
NC-1090	1999	9712	9712	-	71%	-
NC-1129	1999	4693	4458	79%	74%	5%
NC-1135	2002	19770	19213	80%	70%	11%
NC-1116	2004	38311	38171	-	63%	-
NC-1143	2004	11434	11434	-	89%	-

Chapter 3. Clearcutting and Site Preparation, but not Planting, Promoted Early Tree Regeneration in Boreal Alaska[1]

3.1. Abstract

The stand initiation stage decisively influences future forest structure and composition, particularly in the boreal forest which is a stand replacement disturbance driven system. In boreal Alaska, the conventional forest management paradigm of the 20th century focused on production of large-dimension timber, particularly white spruce (*Picea glauca*). However, energy generation from wood is expected to increase, which is likely to expand forest harvest and potentially shift the management focus to fuelwood production. We evaluated the effects of forest harvest management practices on post-harvest regeneration by examining whether management practices of harvest type, site preparation method, and reforestation technique resulted in differences in forest regeneration in terms of species presence, dominance, basal area, and total stem biomass. We recorded presence of white spruce, birch (*Betula neoalaskana*), and aspen (*Populus tremuloides*) by size class, and DBH and height of the three species in 726 plots from 30 harvest units, distributed across harvest and treatment types, harvest year, unit size, and the geographical location of harvests. Analyses were conducted using a stochastic gradient boosting technique (TreeNet algorithm). Our results indicated that management practices suitable/acceptable for biomass differ from the traditional white spruce-focused management. Artificial reforestation does not appear to be superior to natural regeneration in obtaining more stems or producing greater biomass. Clearcutting and/or site preparation increased tree regeneration, basal area, and

[1] Miho Morimoto, Glenn P. Juday, and Brian D. Young, Clearcutting and site preparation, but not planting, promoted early tree regeneration in boreal Alaska. Prepared for submission to New Forests.

biomass when compared to partial harvest and/or no site preparation. Planting of white spruce may only be necessary in specific circumstances, such as in no/low white spruce seed crop years, or in landscapes depleted of seed trees.

Keywords: low-input management, post-harvest regeneration, clearcutting, site preparation, TreeNet (stochastic gradient boosting)

3.2. Introduction

During ecological succession, the stand initiation stage decisively influences future forest structure and composition, particularly in the boreal forest which is primarily a stand replacement disturbance driven system (Chapin et al. 2006a; Foote 1983; Gauthier et al. 2015). Fire is the dominant natural disturbance in North American boreal forest, although various fire suppression policies are in place that modify or limit its effects particularly near communities (Burton et al. 2008; Chapin et al. 2006b). Pre-fire vegetation and fire severity greatly influence post-fire tree regeneration (Foote 1983; Hollingsworth et al. 2013; Johnstone et al. 2010). In particular, the depth of organic layer is one of the most important variables determining the post-fire regeneration trajectory (Johnstone and Kasischke 2005; Shenoy et al. 2011). In Interior Alaska, a thick organic layer tends to accumulate because the rate of organic matter decomposition in soils, particularly in spruce stands, is very slow due to cold temperatures (Valentine et al. 2006). In Alaska, post-fire plant regeneration pathways vary from self-replacement to initial or relay floristics, depending on the depth of organic layer remaining following fire (Johnstone and Chapin 2006; Johnstone et al. 2010). When fire consumes a small amount of the organic layer, regeneration is dominated by previous vegetation that survived belowground and can regenerate asexually from the remaining parts. In contrast, when fire largely consumes the organic layer, burned sites promote establishment of early-successional species that germinate from seeds on exposed mineral soil (Johnstone and Chapin 2006; Johnstone and Kasischke 2005).

Although forest harvest is sometimes seen as a disturbance that produces similar effects to a wildfire on forest ecosystem, the effects are not identical (McRae et al. 2001; Nitschke 2005; Rees and Juday 2002). Numerous studies examining post-fire forest succession are available for Alaska and boreal Canada (Johnstone and Chapin 2006; Johnstone et al. 2004; Johnstone et al. 2011; Purdy et al. 2002; Shenoy et al. 2011; Viereck and Schandelmeier 1980). However, studies of post-harvest tree regeneration are limited (Boateng et al. 2009; Wurtz and Zasada 2001; Youngblood and Zasada 1991).

In central Interior Alaska, a large portion of the most productive boreal forest sites, especially near transportation and population centers, was transferred from federal to state ownership, beginning at statehood in 1959. On these lands the conventional forest management paradigm in the second half of the 20th century focused on production of large-dimension timber, particularly white spruce (*Picea glauca* (Moench) Voss**;** Wurtz and Gasbarro 1996). As a result, several silvicultural systems believed to maximize regeneration and production of white spruce have been studied, including clearcutting (even aged) and partial harvest (uneven-aged) methods combined with various site preparation treatments and assisted tree regeneration (Densmore et al. 1999; Wurtz and Zasada 2001; Youngblood et al. 2011; Youngblood and Zasada 1991). The predominant operational harvest method used in the last several decades has been clearcutting of the mature white spruce-dominated stands, and partial harvest of larger diameter white spruce trees within mixed stands. Within the study region, clearcutting was used widely until the late

1990s (Alaska Division of Forestry 2013a). However, since the 1990s when demand decreased for large-dimension white spruce from the Asian market, the proportion of all harvesting that used the clearcutting silvicultural system has decreased (Wurtz et al. 2006). In the North American boreal forest, there is increasing concern over some effects observed in large clearcuts. For example, in a study in Northern Alberta, clearcuts that exceeded 100 ha experienced low spruce recruitment due to the limited seed dispersal ability of white spruce (Timoney and Peterson 1996). Increasingly clearcutting is used in conjunction with mitigating measures, such as variable retention and carefully planned harvest distribution and layout across the landscape (Franklin et al. 1997).

White spruce is a masting species and produces a large seed crop roughly every 11 years in Interior Alaska (Juday et al. 2003; Roland et al. 2014). As a result, in order to achieve an adequate component of white spruce in regenerating stands, various site preparation treatments (16% of total area harvested) and assisted tree regeneration (44% of total area harvested) have been applied between the years 1972-2012 (Alaska Division of Forestry 2013a). In central Interior Alaska, mechanical site preparation is sometimes applied on a given site in order to enhance seedbed quality and reduce competing vegetation for seedling establishment (Cole et al. 2003; Youngblood and Zasada 1991). White spruce regenerates almost exclusively from seeds, thus seedbed quality is a critical factor for adequate regeneration. Mineral soil substrate is ideal for white spruce regeneration (Zasada and Gregory 1969). In addition, the early growth of white spruce is slower than early-successional species and asexually regenerated species such as Alaska birch (*Betula neoalaskana* Sarg.), quaking aspen (*Populus tremuloides* Michx.), and bluejoint (*Calamagrostis canadensis* (Michx.) P. Beauv.; Youngblood 2012; Youngblood and Max 1992; Youngblood and Zasada 1991). *Calamagrostis* is the major species of concern as a competitor of white spruce regeneration because it spreads rapidly by belowground rhizomes and restricts white spruce seedlings establishment and growth (Lieffers et al. 1993). As a result, when *Calamagrostis* is present prior to harvest, site preparation is typically applied following harvest to remove the organic layer and belowground rhizomes of competitive vegetation (Wurtz and Zasada 2001; Youngblood et al. 2011). Additionally, when state minimum stocking standards are not met or not expected to be met, forest managers often require planting white spruce seedlings (Alaska Division of Forestry 2008).

In Interior Alaska, the use of wood for home heating and energy generation is expected to increase due to escalating fuel prices (Fresco and Chapin 2009). As of 2015, nine wood biomass energy facilities have been built in Interior Alaska with another ten under construction, and more than eleven are in design or feasibility status (Alaska Energy Authority 2015). Energy demands for woody biomass are likely to expand forest harvest and change the conventional forest management paradigm (production of large-dimension timber). Such a shift, in fact, has already begun with increased birch harvest for firewood, and with aspen being used as feed stock in wood pellet and fabricated log production (Alaska Division of Forestry 2013a). In addition, harvest cycle is likely to be shorter for biomass harvest than for large-dimension wood products, requiring more frequent regeneration over a given period of time (Janowiak and Webster 2010). In order to meet the needs of this evolving forest management situation, it is crucial to understand post-harvest regeneration over the long term for not just white spruce, but other species as well, to ensure sustained yield wood production.

The total area harvested in this part of the boreal forest is relatively small compared to boreal Canada, Fennoscandia, and Russia (Burton et al. 2006; Larsson and Danell 2001; Timoney and Peterson 1996). However, over 40 years of regeneration under systematic silvicultural practices has been accumulated. Although unconstrained logging occurred in the early 1900s near a few early populations centers and gold mines (Wurtz et al. 2006), in this study we analyze only the last 40 years of post-harvest regeneration because of the lack of records before that time period (Roessler 1997). The objective of this study is to evaluate the effects of harvest methods over the past 40 years and the subsequent management practices on post-harvest tree regeneration in central Interior Alaska. To achieve this objective, we evaluated the harvest type, site preparation method, and reforestation techniques utilized in order to assess the differences in forest regeneration outcomes in terms of species presence, dominance, basal area, and total woody biomass. There are a few studies examining the effects of various harvest and reforestation practices on post-harvest regeneration in Interior Alaska, but those have occurred on small experimental plots (Wurtz and Zasada 2001; Youngblood 2012; Youngblood et al. 2011; Youngblood and Zasada 1991). This study is the first landscape-scale study in central Interior Alaska to examine both temporal and spatial effects of mature forest harvest on regeneration in an operational context.

3.3. Methods

3.3.1. Study area

The study was conducted within the Fairbanks and Kantishna Management Areas of the Tanana Valley State Forest and state forest classified land ("state forest lands"; Figure 3.1) which covers 578,575 ha. The study area is within Interior Alaska boreal forest, stretching from the Alaska Range in the south to the Brooks Range in the north, and Canadian border in the east to the Chukchi Sea in the west, covering approximately 47 million ha (Figure 3.1). Interior Alaska boreal forest is composed primarily of white spruce, black spruce (*Picea mariana*

(Mill.)), Alaska birch, quaking aspen, with minor amounts of balsam poplar (*Populus balsamifera*), and tamarack (*Larix laricina*; Labau and van Hees 1990). The most extensive forest cover types on state forest land are black spruce and mixed white spruce-hardwood types (Hanson 2013). Although black spruce forest type is the most extensive, it generally occurs on low-productive, permafrost underlain soils resulting in low productivity (Hanson 2013). In contrast, white spruce types often occur on the most productive sites resulting in high productivity (Hanson 2013). Soils are mostly silt loams formed from loess parent material (Ping et al. 2006) and elevations range from 100 m to 600 m.

Climate of the study area is strongly continental and varies substantially across topographic factors, including elevation and aspect (Shulski and Wendler 2007). The principal long-term NWS First Order station for the study area is Fairbanks International Airport (1948-present; 133 m). The Fairbanks Airport climate record is a single point record taken on a grass surface near the runway (not forest). Due to the general lack of long term climate measurements in Alaska, the Airport climate record is traditionally used as one reference point in a number of analyses of climate trends and forest growth studies (Juday and Alix 2012; McGuire et al. 2010; Wilmking et al. 2004). Mean annual temperature at Fairbanks Airport is -2 °C and annual precipitation of 270 mm, with extreme temperatures ranging from -50 °C to 35 °C. The period between freezing temperatures in the early 21st century is approximately 123 days at Fairbanks, an increase from 85 days in the early 20th century (Wendler and Shulski 2009). However, climate in the region varies substantially according to factors such as elevation and aspect (Shulski and Wendler 2007). Geographically continuous, locally relevant climate data have been generated by downscaled modeled climate data for the study area (SNAP 2015). Temperature inversion is a major factor that create great temperature variabilities across elevation, specifically in winter (Shulski and Wendler 2007). Aspect also affects temperature variability because of the low-angle of the sun (Shulski and Wendler 2007). South-facing slopes are generally warmer and drier compared to north-facing slopes that are cold and wet, and often underlain by permafrost (Shulski and Wendler 2007).

3.3.2. Silvicultural systems

The two primary harvesting methods utilized within the study region on the Fairbanks and Kantishna areas of state forest lands were clearcutting and various partial cutting systems. Both of these systems were used for green wood and post-fire salvage harvests. The clearcut system, as utilized in the study area, ranged from a conventional clearcut, to a clearcut with reserves (The Society of American Foresters 1994). Partial cuts typically involved one of two types: the removal of a single species from mixed stands, predominantly white spruce, or an intermediate harvest with diameter limits (Alaska Division of Forestry 2008). Regardless of the harvest system, only whole tree harvesting was performed. All sampled regeneration units examined in this study were dominated by the mature white spruce type before harvest. These natural stands in turn originated from either wildfire or primary succession following flooding (Alaska Division of Forestry 2013a). Although harvest of other species is likely to increase in the future, white spruce has been the major harvested species in the study area. As a result, this study examined only units that were either clearcut or partial cut for spruce. Partial harvest units of hardwood types or post-fire salvage logging were excluded. All harvest units sampled were cut once between 1975 and 2004 and were not burned during the period from immediately following harvest to the year sampled (2013 or 2014).

In order to enhance seedbed quality for white spruce germination, mechanized site preparation is often applied in central Interior Alaska (Youngblood et al. 2011; Youngblood and Zasada 1991). The site preparation treatments used in this study involved mechanical scarification using either a bulldozer blade or a disk trencher (Alaska Division of Forestry 2013a). We categorized harvest units that received any site preparation as scarified regardless of the method used.

All harvest units relied either on natural regeneration, white spruce artificial regeneration, or small amounts of planted exotic conifers. Within the study area, the two most common artificial regeneration techniques were planting of container stock using locally sourced seeds or direct seeding (Alaska Division of Forestry 2000). In this study, we included only harvest units that experienced natural regeneration or planting of white spruce seedlings from container stock.

Within the study region, historical harvest units vary in size from ~ 1 to a few hundred ha (Figure 3.2a). The size distribution of the harvest units was positively skewed, with a median of 4.66 ha and a mean of 10.89 ha. In this study, we excluded the smallest units (< 1 ha) and extremely large units (> 40 ha) because of the small number of units in these size ranges. As a result, the harvest units included in this study ranged from 1.4 – 30.3 ha in size (Figure 3.2b). The total area sampled was 269 ha, accounting for approximately 3.5% of the total 7,000 ha harvested in the Fairbanks and Kantishna areas of state forest lands in Interior Alaska (Alaska Division of Forestry 2013a).

3.3.3. Sampling design

We investigated 30 separate harvest units located in the Fairbanks and Kantishna areas of state forest lands from the Fairbanks office of the Alaska Department of Natural Resources

Division of Forestry (AKDOF) Forest Management Database (FMD; Alaska Division of Forestry, 2013a; Appendices 3. and 3.). The FMD is a GIS-based database which includes the location and types of all forest management activities that has occurred on state lands within the Fairbanks and Kantishna areas (see Figure 3.1) since 1972. Using this database, we selected representative harvest units that were evenly distributed across harvest types (16 clearcut and 14 partial cut units), site preparation methods (11 scarified and 19 unscarified units), reforestation techniques (16 planted and 14 naturally regenerated units), year of timber sale, and size of harvest units (Figure 3.2b). Sample harvest units were also selected to achieve wide geographical coverage across the study region (Figure 3.1, Table 3.1). To quantify tree regeneration, we used 1.69 m radius circular plots, the same plot size as operational AKDOF reforestation surveys (Alaska Division of Forestry 2008). We determined plot sampling intensity based on a preliminary test of sampling efficiency using a censused population of white spruce located in the study region (Juday 2012). Based on this analysis, we used four 1.69 m radius circular plots ha^{-1} as our sampling intensity. To determine the placement of plots, we created a virtual 50 m × 50 m grid with points at the center of each cell over the entire study area using the Fishnet tool (ArcGIS 10.2; ESRI 2013; Figure 3.3). The points falling within the selected harvest units represented the center of the plots. The number of plots in each unit varied between 7 and 120 due to the size and geographic configuration of the harvest units (Table 3.1). We prioritized sampling a large number of harvest units over intensive sampling in a single harvest unit to cover a greater geographic area, and allow more replications of management practices and years. Because of this strategy, when the calculated number of plots was greater than 50, the sampling intensity was truncated to 50 or fewer by sampling every other or every third plot. In units where only every other plot was sampled, sampled plots were evenly distributed starting from the first plot (Figure 3.3). The coordinates of the plots (+/- 1m) were exported to Trimble Pro XT GPS unit (Trimble Navigation, California) and were used to navigate to the sample plot centers in the field.

3.3.4. Data collection and preparation

3.3.4.1. Response variables

Field sampling was conducted during the summers of 2013 and 2014. Within each plot, we counted all live white spruce which did not have diameter at breast height (DBH), and live birch, aspen, balsam poplar, and black spruce < 1cm in DBH (Figure 3.4). When a live white spruce crossed the DBH plane, we measured total height and DBH. We measured DBH and height if live birch, aspen, balsam poplar, and black spruce were 1cm or greater in DBH. Residual stems were distinguished from regeneration based on estimated age of the tree, and excluded from analysis. The sampling protocol for this study will be made available at Bonanza Creek Long Term Ecological Research Site website (http://www.lter.uaf.edu/).

Although our response variables were initially collected as continuous variables, we categorized the variables into binary classes to obtain high accuracy for robust and reliable inferences. We predicted presence/absence for an "all size" group and for a sapling group (DBH > 2.5 cm) of white spruce, birch, and aspen. We identified dominant species in each plot in terms of stem density, and assigned 1 (dominant) or 0 (not dominant) to each species by the size class. If the stem density of different species was the same, and a third species was either absent or present at lower density, both species were classified as dominant (assigned 1). Basal area and biomass were categorized into 1 (high) or 0 (low). For basal area, we set thresholds of 0.5, 1, and 0 m^2 for white spruce, birch, and aspen, respectively, so that the binary classes are well balanced.

For woody biomass calculation, we used biomass equations established using samples from Interior Alaska (Yarie et al. 2007). The equations follow the form:

$$Y = \alpha_1 \cdot DBH + \alpha_2 \cdot DBH^2 + \alpha_3 \cdot height \qquad \text{(Equation 3.1)}$$

where Y is the total above ground biomass (grams), and α_1, α_2, and α_3 are specific empirically determined coefficients for each species. We combined biomass accumulation of each woody species (white spruce, birch, aspen, balsam poplar, and black spruce) and the aggregated biomass accumulation was categorized into high (≥ 5 t·ha^{-1}) and low (< 5 t·ha^{-1}).

3.3.4.2. Predictors

We obtained the values of field predictors at the center of a 50 m × 50 m lattice grid (Figure 3.3). The predictors were either publicly available or obtained from AKDOF. We chose the best available data from the publicly available data. It is important to recognize that the resolutions are different among predictors, which might affect prediction and its accuracy. All the predictors are listed in Table 3.2. Type and year of harvest, site preparation, and reforestation, and size of harvest unit were obtained from the FMD (Alaska Division of Forestry 2013a). Elevation (m), aspect, slope (degree), and topographic position index (TPI) were obtained from a 5-m resolution digital elevation model (DEM) created by Geographic Information Network of Alaska (GINA) in ArcGIS. This DEM has 90% probability of 3 meter vertical accuracy, and 90% probability of 12.2-meter horizontal accuracy. The GIS data and metadata for the DEM are available at http://ifsar.gina.alaska.edu/. Aspect was transformed using the following equation;

$$(1 - \cos(2\pi \times aspect / 360)) / 2 \qquad \text{(Equation 3.2)}$$

where aspect is measured in degrees. Slope was considered flat when it was smaller than 5 degrees. TPI was calculated using Land Facet Corridor Designer, v. 1.2.884 tool (Jenness et al. 2013) in ArcGIS.

We used the AKDOF forest type map (see details in Hanson, 2013; Alaska Division of Forestry, 2013b) to calculate distances (m) from each plot within a harvest unit to various features with the "Generate Near Table" tool in ArcGIS. The features include stands of white spruce forest, birch forest, aspen forest, water features, highways, forest roads, developed area, and urban area (Alaska Division of Forestry 2013b). The forest type layer was created based on field measurements and aerial photo interpretations (Hanson 2013). In some cases, the sampled harvest unit might have had a white spruce stand closer than indicated on the current forest type layer because of harvest in the landscape surrounding the sampled unit. In such cases, harvests nearest to sample units were considered white spruce forests if they were harvested eight years or more following the harvest of the sample units. We used eight years because white spruce most likely produces medium to large seed crops every seven years (Roland et al. 2014). We assigned soil subgroups to each plot in ArcGIS using soil maps obtained from the USDA Natural Resources Conservation Service (map and metadata available at http://websoilsurvey.nrcs.usda.gov/).

Downscaled historical average monthly temperature and monthly precipitation from 1975-2009 were obtained from the Scenarios Network for Alaska + Arctic Planning (http://www.snap.uaf.edu/data.php). The resolution of downscaled climate data is 771 m. We used climate data of the growing season (May-August) because tree growth is greatly affected by climate variables of these summer months (Beck et al. 2011; Juday and Alix 2012; Lloyd et al.

2013; Wilmking et al. 2004). We averaged mean monthly temperatures and total monthly precipitation of twenty years post-harvest, which is the most critical time period for tree regeneration (Van Cleve et al. 1996).

3.3.5. Statistical analysis

Due to the complex and multivariate nature of the data, we used the non-parametric TreeNet algorithm to predict post-harvest regeneration (Friedman et al. 2000) as implemented in the Salford Predictive Modeler version 7 (Salford Systems 2013a). This type of model does not require the same set of assumptions as frequency statistics, such as normality and independence, which are typically violated within ecological data (Betts et al. 2009; Breiman 2001). TreeNet is known to produce highly accurate predictions even with noisy data (Ohse et al. 2009). The TreeNet algorithm is often used for prediction, but it is also a powerful tool to mine data and identify relationships between a response variable and predictors by creating partial dependence plots in multivariate settings (Breiman 2001). As a consequence, we chose the TreeNet algorithm to identify the effects of management practices, including harvest, site preparation, and reforestation, on post-harvest regeneration. Although our focus was on the effects of management practices, we built predictive models using all available environmental variables (Table 3.2) to improve predictive accuracy and to place our results in a greater ecological context for a robust inference.

To construct the decision trees used by TreeNet, a balanced option which rebalances unequal class sizes was selected (Salford Systems 2013b). We decided to grow 1,000 trees but the actual number of trees generated was optimized by the program for each predictive model (Salford Systems 2013b). For validation purposes, we used the testing method of cross-validation with a randomly selected 10% sample. All other options were set at program default values (Salford Systems 2013b) which are known to perform well. The model performances were evaluated by applying the predictive model to the complete data set, and obtaining average accuracy and area under the receiver operating characteristic (ROC) curve (AUC). The average accuracy is an average of classification accuracies of each class. The ROC curve demonstrates the performance of a binary classifier system by plotting the true positive rate against the false positive rate at different discrimination thresholds (Hastie et al. 2009). A perfect model will score an AUC of 1, while random guessing will score an AUC of around 0.5 (Metz 1978).

In order to examine the effects of management practices on post-harvest regeneration, we evaluated relative variable importance and created partial dependence plots. The importance value for any predictor is determined by averaging the number of times it is selected as a tree node over all trees and squaring improvements in error rate resulting from these nodes (Hastie et al. 2009). A relative importance value of 100 is assigned to the most important predictor, and relatively scaled values are assigned to other predictors based on the most important predictor. Partial dependence plots show the relationship between the response and any given predictor by representing the dependence of the response on the predictor variable when all other variables are held at their mean (Hastie et al. 2009).

3.4. Results

The TreeNet algorithm predicted species presence/absence, species dominance, basal area, and biomass at high accuracy (Table 3.3). AUC for each prediction was mostly over 0.8. The main exceptions were the AUC for presence/absence of white spruce and birch “all size” group, which were slightly under 0.8 (Table 3.3). Predictive models of aspen displayed the highest accuracy and AUC among the three species evaluated here. For aspen, AUC values were all above 0.9 (Table 3.3). The prediction of white spruce was the least successful for all variables except for presence/absence of the "all size" group. However, even for spruce the AUC values were above 0.8 except for one case (Table 3.3). The model performances were higher for saplings than the "all size" group for both presence/absence and dominance of all species (Table 3.3). For each species, the prediction was most successful for basal area among all the variables (Table 3.3). Predictive accuracies were well balanced between two classes (Table 3.3). It appears that the TreeNet algorithm provided reproducible and robust models, and findings, in our data set, while not violating assumptions as other methods would likely do at a similar sampling intensity.

The different management practices, including harvest type, site preparation, and reforestation, were generally not found to make as great a contribution to accurate predictions as the environmental variables (Figure 3.5a-f). This indicates a smaller effect due to the management practices on post-harvest regeneration than that of the environmental variables. In general, management practices had greater effects on saplings than on stems of the "all size" group for white spruce and aspen, as indicated by the higher relative importance values for saplings (Figure 3.5a-d). The relative importance of management practices for white spruce and aspen varied, but the importance was generally low for birch (Figure 3.5a-e). Year of harvest was one of the most important predictors for presence and dominance of the sapling group, basal area, and biomass (Figure 3.5a-f).

The TreeNet algorithm depicted the trend in species presence/absence, species dominance, basal area, and biomass in response to harvest type, site preparation method, reforestation technique, and year of harvest (Figure 3.6). White spruce presence, dominance, and basal area tended to be greater in clearcut, scarified, and planted units than in partial cut, unscarified, and naturally regenerated units, except that site preparation did not appreciably contribute to the dominance of "all size" group (Figure 3.6a-e). White spruce presence in the "all size" group was lower in units that were logged within 25 years and higher in units that were logged 25-35 years before, but became lower again after 35 years of harvest (Figure 3.6a). White spruce sapling presence was higher in units with longer time since harvest (Figure 3.6b). White spruce dominance of "all size" group was greater in units with shorter time since harvest, while white spruce sapling dominance was greater in units with longer time since harvest (Figure 3.6c-d). White spruce basal area was low until 15 years after harvest, and became high after that time period (Figure 3.6e).

Clearcutting resulted in greater birch presence, birch sapling dominance, but lower birch "all size" group dominance and birch basal area (Figure 3.6a-e). Birch sapling presence and "all size" group dominance were greater in scarified than in unscarified units, while birch sapling dominance and birch basal area were greater in unscarified than in scarified units (Figure 3.6b-e). Birch dominance and basal area were greater in planted units than in naturally regenerated units (Figure 3.6c-e). Birch presence, sapling dominance, and basal area were low in units harvested 15 or fewer years before our sampling, and much greater in units harvested more than 15 years before sampling (Figure 3.6a, d, e). Dominance of birch in the "all size" group was greatest in units harvested 20-25 years or earlier (Figure 3.6c).

Aspen presence, dominance of sapling, and basal area were greatest in clearcut and scarified units (Figure 3.6a, b, d , e), although aspen dominance of "all size" group was greater in unscarified than in scarified units (Figure 3.6c). However, the effects of type of harvest and site preparation were limited on aspen "all size" group (Figure 3.5, Figure 3.6a, c). Planting spruce seedlings resulted in a lower aspen dominance and basal area, but slightly greater aspen presence (Figure 3.6a-e). Aspen presence and dominance of “all size” group were greater in units that were logged more recently, while aspen presence and dominance of saplings, and basal area were greater in units that were logged in earlier years (Figure 3.6a-e).

Biomass tended to be greater in clearcut and/or scarified units than in partial cut and/or unscarified units (Figure 3.6f). Reforestation technique (planted vs. natural regeneration) did not contribute to biomass prediction (Figure 3.5f). Year of harvest was the most important variable for the biomass prediction (Figure 3.5f). Biomass accumulation was low until 15 years after harvest, and became high after 20 years post-harvest (Figure 3.6f).

3.5. Discussion

The trends identified in post-harvest regeneration using a robust TreeNet algorithm provide a useful basis for forest harvest management. However, the predictions need to be interpreted with a recognition of varying contributions of each variable to each prediction indicated by the relative variable importance (Figure 3.5). Harvest type, site preparation technique, and reforestation methods were not the most important among all 27 predictors. In particular, the reforestation method was one of the least important predictors for the three different species studied here (Figure 3.5). In addition, the management practices all had relatively low importance in predicting any responses for birch (Figure 3.5). These results indicate that post-harvest regeneration outcomes cannot be successfully evaluated by management practices alone. However, harvest type and site preparation had relatively high importance particularly in predicting saplings and basal area of white spruce and aspen (Figure 3.5a-e), and were associated with trends in post-harvest regeneration (Figure 3.6).

The effect of harvest type on post-harvest regeneration was relatively consistent with the inference that clearcutting resulted in greater presence, dominance, and basal area of white spruce and aspen of any size groups, and greater presence of birch of any size groups when compared to partial cutting. The effect of harvest type was greater on sapling presence, dominance, and basal area than "all size" group for both white spruce and aspen (Figure 3.5a-d). Clearcutting supported greater biomass accumulation (up to 40 years) than partial cutting, because of the overall greater predicted presence of the 3 species and greater basal area of trees in clearcuts than partial harvest stands (Figure 3.6). Both white spruce and aspen experience optimal growth under full light conditions (Nienstaedt and Zasada 1990; Safford et al. 1990), which were created by clearcutting. Clearcutting also promotes aspen suckering (Perala 1990). Although greater growth of white spruce in clearcuts is consistent with results from individual research plots in Interior Alaska (Youngblood and Zasada 1991) and in Alberta boreal mixed wood (Solarik et al. 2010), our results now demonstrate that this effect was also achieved at the operational and landscape scale.

On the other hand, although birch was more likely to appear in clearcuts than in partial cuts, birch dominance of the "all size" group and birch basal area were greater in partial cuts than in clearcuts (Figure 3.6). This result is somewhat inconsistent with previous studies that demonstrate greater growth of birch under greater amounts of sunlight often present in clearcuts (Marquis et al. 1964; Perala and Alm 1990a; Perala and Alm 1990b; Safford et al. 1990). There was perhaps less competition in partial cuts than in clearcuts due to the lower presence and dominance of regenerating white spruce and aspen, which could have allowed greater birch dominance and growth. Even so, the contribution of harvest type to predictions of birch in harvest regeneration outcomes was low, and so environmental factors appear to affect birch regeneration more than harvest type.

Although we found that clearcutting resulted in greater subsequent white spruce presence, it should be noted that a lack of seed trees can become a limiting factor for white spruce regeneration (Greene et al. 1999; Timoney and Peterson 1996). During mast years, white spruce seeds are wind dispersed, with the greatest number of seeds falling within 100 to 150 m from the source tree (Youngblood and Max 1992). Timoney and Peterson (1996) found that in boreal Canada spruce recruitment following clearcutting was poor due to the size of the clearcut (most clearcuts exceeded 100 ha). In contrast, in Interior Alaska clearcut sites supported similar white spruce regeneration density as units that received a shelterwood harvest, a regeneration harvest technique that leaves white spruce seed trees on the harvest site (Wurtz and Zasada 2001). The size of clearcut units was only 1.3 ha in earlier shelterwood study (Wurtz and Zasada 2001). Such small clearcuts provide ample opportunities for unharvested trees outside the units to disperse seeds into the units. Because most clearcut units in our study were smaller than ~ 10 ha (Figure 3.2), it is reasonable to infer that similar seed dispersal processes took place in the operational harvests as in the shelterwood research study. Our analysis of the configuration of the sampled harvest units shows that over 90% of plots were within 100 m of the harvest unit perimeter, with the greatest distance of 150 m. Harvest units in reality rarely approached a circular configuration, which for a unit of 10 ha in size would create a maximum distance from the harvest edge of 180 m. This means that in our sampled regeneration units of 10 ha or smaller, the actual distance from the harvest perimeter was generally much less than 180 m. Therefore, we tentatively conclude that harvests smaller than ~ 10 ha would, for the most part, not need retained seed trees within the harvest stands for white spruce regeneration.

In Interior Alaska, although profound negative effects of clearcutting have not been found, the major harvest method has been shifting from clearcutting to partial cutting primarily due to social and ecological concerns about clearcutting which have been reported in other boreal regions. In Interior Alaska clearcutting at the current (small) scale does have some advantages compared to partial cutting, particularly because clearcutting appears to promote regeneration, and is more operationally efficient and thus more economical (Keenan and Kimmins 1993). In addition, clearcutting in general has to be small because of the predominantly small size of pure white spruce stands that are the main target of harvest. On the other hand, clearcutting (in the literal sense of complete tree removal) removes some legacy forest structures that are important to wildlife or ecological value that could be retained in a partial cutting system.

Site preparation resulted in greater presence, dominance, and basal area of spruce, birch, and aspen in most cases (Figure 3.6). Site preparation has been widely demonstrated to enhance seedbed quality for tree regeneration (Gartner et al. 2011; Safford et al. 1990), thus promoting more vigorous trees that can achieve higher rates of both below- and above-ground growth. Several experimental studies in Interior Alaska have reported that site preparation results in higher density and/or growth of white spruce (Cole et al. 2003; Wurtz and Zasada 2001; Youngblood et al. 2011; Youngblood and Zasada 1991), and in the boreal forest of Canada (Boateng et al. 2009; Calogeropoulos et al. 2004). Our study now establishes that these gains are also achieved in operational practices up to 40 years following harvest. Moreover, site preparation also appears to have positive effects on birch and aspen regeneration. The increases in the presence and basal area of birch and aspen due to site preparation appear to be the result of exposure of a mineral soil substrate compared to the undisturbed forest organic layer (Perala 1990; Safford et al. 1990). One exception to this however appears to be the lower dominance of birch saplings and the aspen “all size” group on scarified compared to unscarified sites (Figure 3.6). This reversal of the general scarification effect appears to be related to the greater dominance by other species, and the relative importance of site preparation on these response variables was low, indicating the magnitude of differences were small (Figure 3.5). In general, site preparation following harvest promoted greater tree establishment and growth, which subsequently resulted in greater biomass accumulation (Figure 3.6).

While we found that site preparation typically results in greater success of regeneration, site preparation can at times result in stunted stems and roots due to intense competition during stem exclusion phase (Wurtz and Zasada 2001). For example, unit NC-305 in our study supported very dense white spruce regeneration, 31,814 ± 12,558 stems$\cdot$ha^{-1}. This unit was logged in 1987, followed immediately by site preparation, during a year of exceptionally large white spruce seed production (Roland et al. 2014). Although the amount of biomass in this unit was greater than the average in other harvest units, the mean diameter of regenerated stems was low, so that many years of additional growth will be required to produce harvestable material. In such a case, the optimal management approach might be to limit site preparation during the mast year. In order to do this, white spruce cone crops can be estimated by the previous year’s seed production and visual inspection of bud primordia (Gartner et al. 2011; Lamontagne and Boutin 2007).

For the last few decades, foresters in Interior Alaska have used assisted regeneration techniques for white spruce (Alaska Division of Forestry 2013a) in order to sustain the species on some sites and promote large, well-positioned trees from the earliest stage of stand development. In fact, planting white spruce seedlings did result in greater white spruce presence, dominance, and basal area. However, the effects of planting on white spruce regeneration overall were very low (Figure 3.5a-e). In addition, dominance and basal area of aspen were lower in planted units than in naturally regenerated units (Figure 3.6), and reforestation did not contribute to prediction of biomass accumulation (Figure 3.5f). This result suggests that planted spruce seedlings suppressed natural regeneration of other species, although we cannot explicitly conclude this because of the low relative importance of the reforestation predictor term, and we do not have direct measurements of suppression. Due to the fact that planting white spruce seedlings is the most expensive post-harvest regeneration procedure, foresters should carefully evaluate the necessity of planting white spruce, and use this technique primarily in circumstances where the benefits are most likely to outweigh such undesired effects. Such circumstances include a management goal of producing large dimension white spruce in the shortest possible time, or regenerating spruce when no/low white spruce seed crop is present or predicted. On the other hand, if the goal is to produce biomass for energy generation, or to retain natural genetic diversity, then planting white spruce seedlings might have no or even potentially adverse effects.

The year of timber harvest was one of the most important predictors for many of our models, especially in determining basal area and biomass accumulation (Figure 3.5), because tree size clearly correlates with time since harvest. As expected, basal area and biomass tend to increase over time in the modeled prediction (Figure 3.6). Presence and dominance of the sapling group (DBH > 2.5 cm) also increase up to 40 years following harvest for all species as a result of tree growth (Figure 3.6). However, presence and dominance of trees of the “all size” group did not show a simple trend like those of saplings (Figure 3.6). In the early stage of regeneration, tree recruitment, growth, and mortality occur at different rates for each species, resulting in variability through time in the presence and dominance of seedlings. In addition, white spruce recruitment varies greatly by year due to its sporadic seed production cycle (Roland et al. 2014).

White spruce presence appears to increase up to 35 years following harvest, birch presence appears to increase up to about 25 years and then decline, but aspen presence shows a clear trend of decreasing for the entire study period (Figure 3.6). This reflects the early growth rate and the level of shade tolerance of each species (Nienstaedt and Zasada 1990; Perala 1990; Safford et al. 1990). White spruce has the slowest growth rates of the species measured in this study and is the most shade tolerant, while aspen has the fastest growth rates and is the least shade tolerant (Nienstaedt and Zasada 1990; Perala 1990; Safford et al. 1990). White spruce seedling recruitment seems to have continued for a longer period than birch and aspen which are both shade-intolerant species that grow rapidly after disturbance (Perala 1990; Safford et al. 1990). The more shade intolerant aspen begins the self-thinning process earlier than birch (Figure 3.6). Birch regeneration appears to be determined largely by time since harvest and only marginally by management practices, suggesting that birch regeneration is barely affected by the environmental changes created by management practices.

The results of this study provide an important quantitative basis for future management planning. Management practices suitable or acceptable for some forms of biomass production appear to be different than practices traditionally used in the region for conventional spruce-focused management. In our study area artificial reforestation does not appear to be superior to natural regeneration in obtaining more stems or producing greater biomass. However, clearcutting and site preparation consistently are associated with increased tree regeneration and greater basal area and biomass. As a result, clearcutting and site preparation are adequate as regeneration techniques, and planting white spruce may only be necessary in specific circumstances, such as in no/low white spruce seed crop years, or in landscapes depleted of seed trees. Finally, when biomass production of any species is the management goal, a shift from spruce harvest to birch may be possible, because birch regeneration is likely to be faster and more abundant without the additional effort required for white spruce establishment.

3.6. Acknowledgements

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3.8. Figures

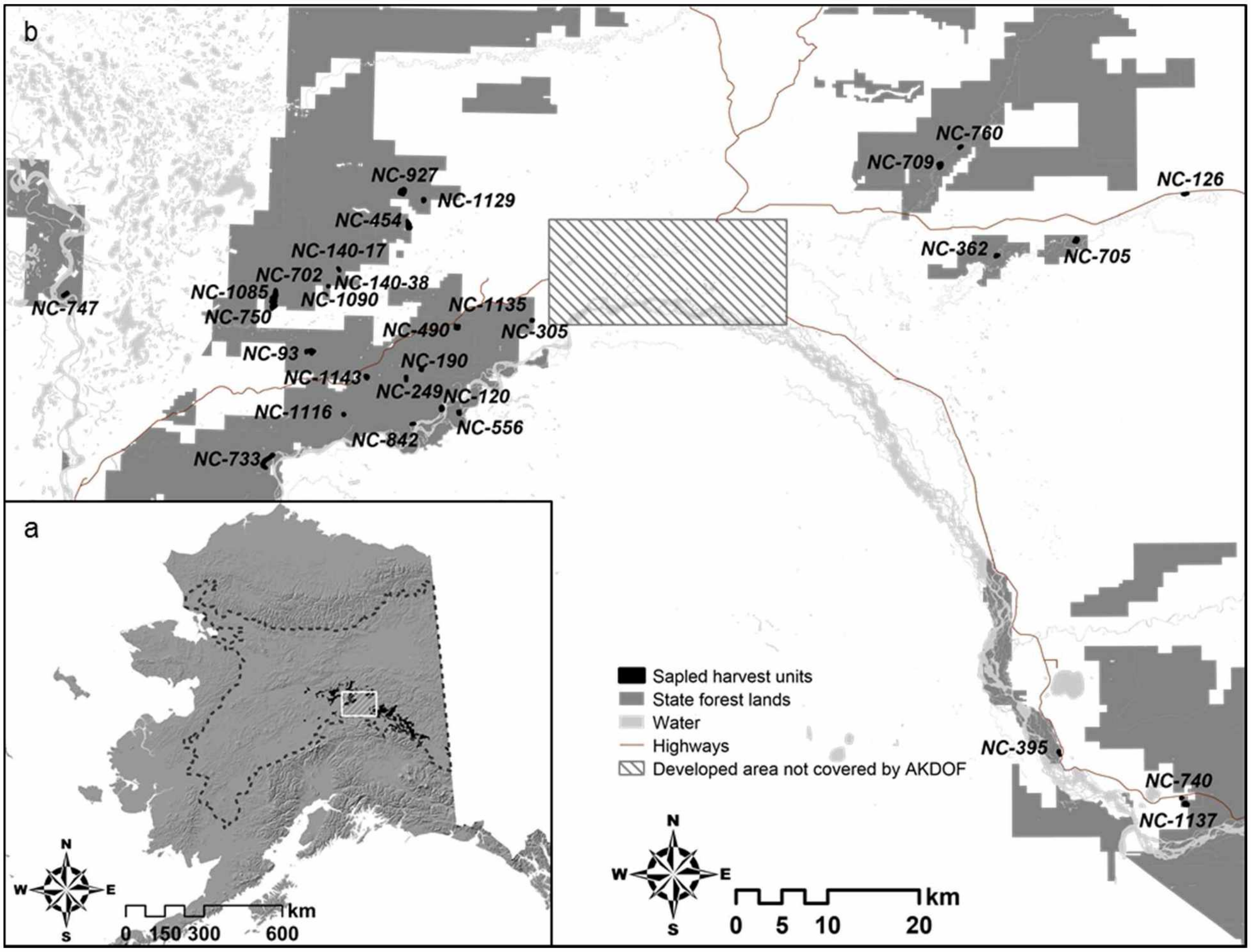

Figure 3.1 Map of study area. (a) Study area (white box) is on state forest lands (black polygon) within Interior Alaska boreal region (dashed line; Nowacki *et al.*, 2001). (b) Sampled harvest units are distributed within Kantishna and Fairbanks areas of Tanana Valley State Forest and forest classified lands. NC- followed by number are sampled harvest units number.

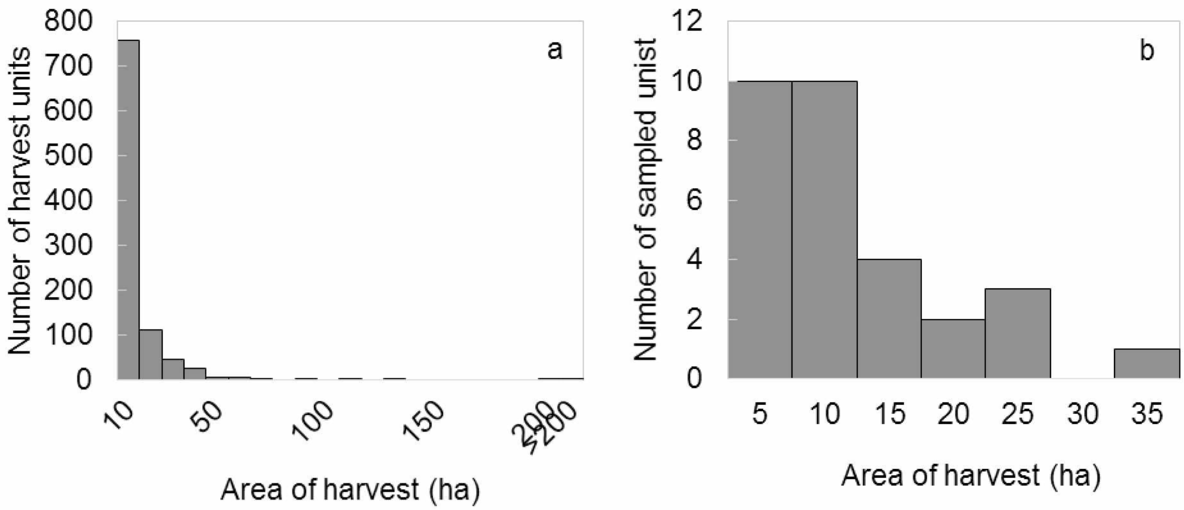

Figure 3.2 Histogram of harvest size of (a) historical harvest units, and (b) sampled harvest units in the Kantishna and Fairbanks areas of Tanana Valley State Forest and forest classified lands. The data was obtained from Alaska Division of Forestry Forest Management Database (Alaska Division of Forestry 2013a).

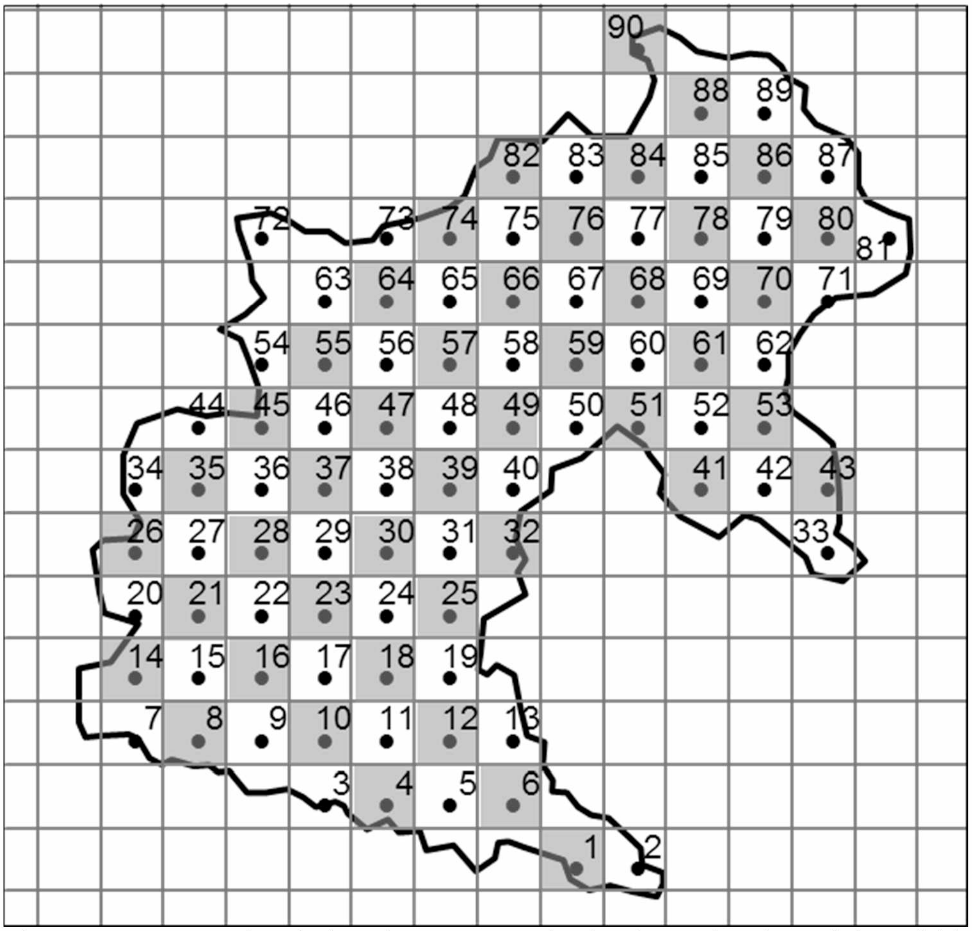

Figure 3.3. Example of plot placement and selection. The size of the grid is 50 m. Dots represent plots and the numbers above them represent plot labels. In units with more than 50 plots, every other plot was selected (shaded cells).

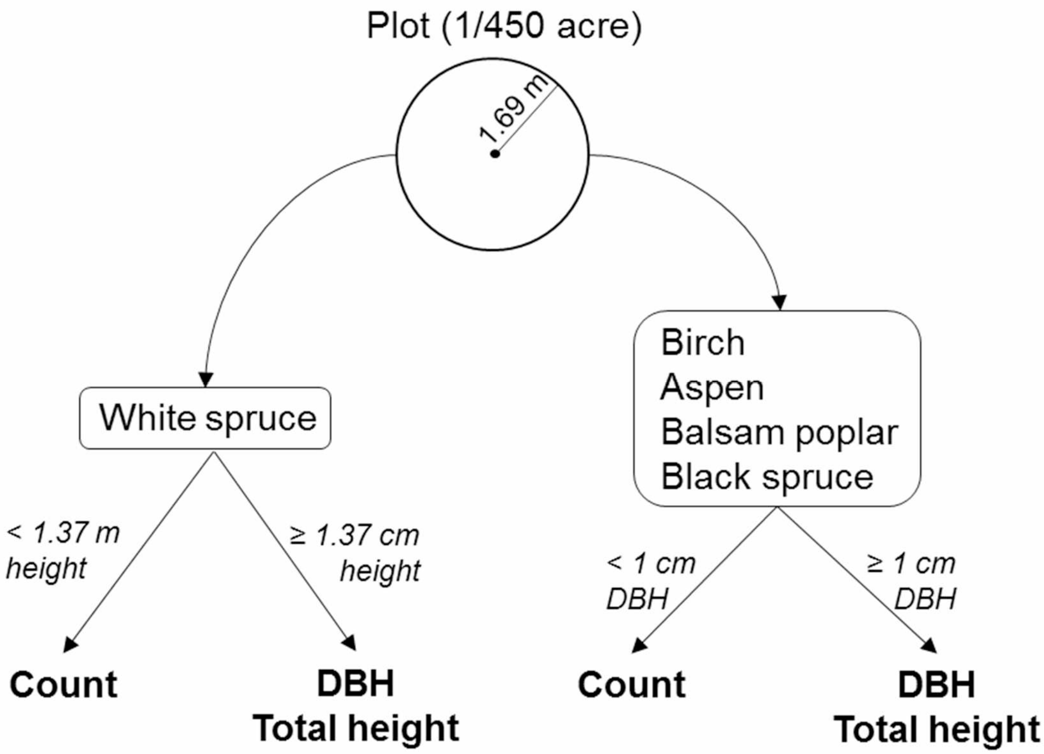

Figure 3.4 Workflow for the field sampling protocol.

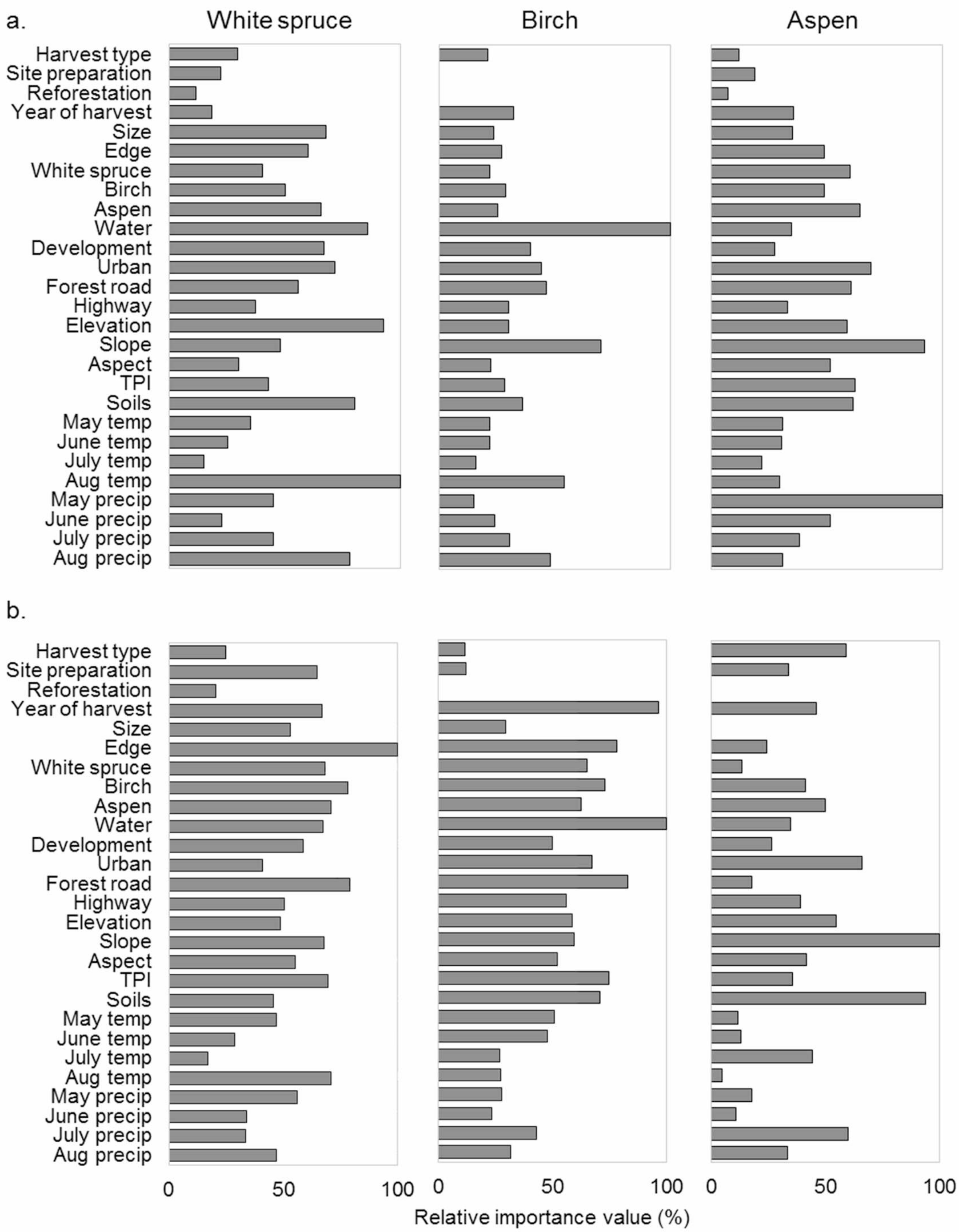

Figure 3.5 Relative variable importance of predictors in the predictive models of (a) presence/absence of "all size" group, (b) presence/absence of saplings, (c) dominance of "all size" group, (d) dominance of saplings, (e) basal area, and (f) biomass. The importance value for any predictor is determined by averaging the number of times it is selected as a tree node over all trees and the squared improvements in error rate resulting from these nodes (Hastie et al. 2009). A relative importance value of 100 is assigned to the most important predictor, and relatively scaled values are assigned to other predictors based on the most important predictor. Missing bars mean that the TreeNet algorithm found the predictor to be zero importance on the prediction.

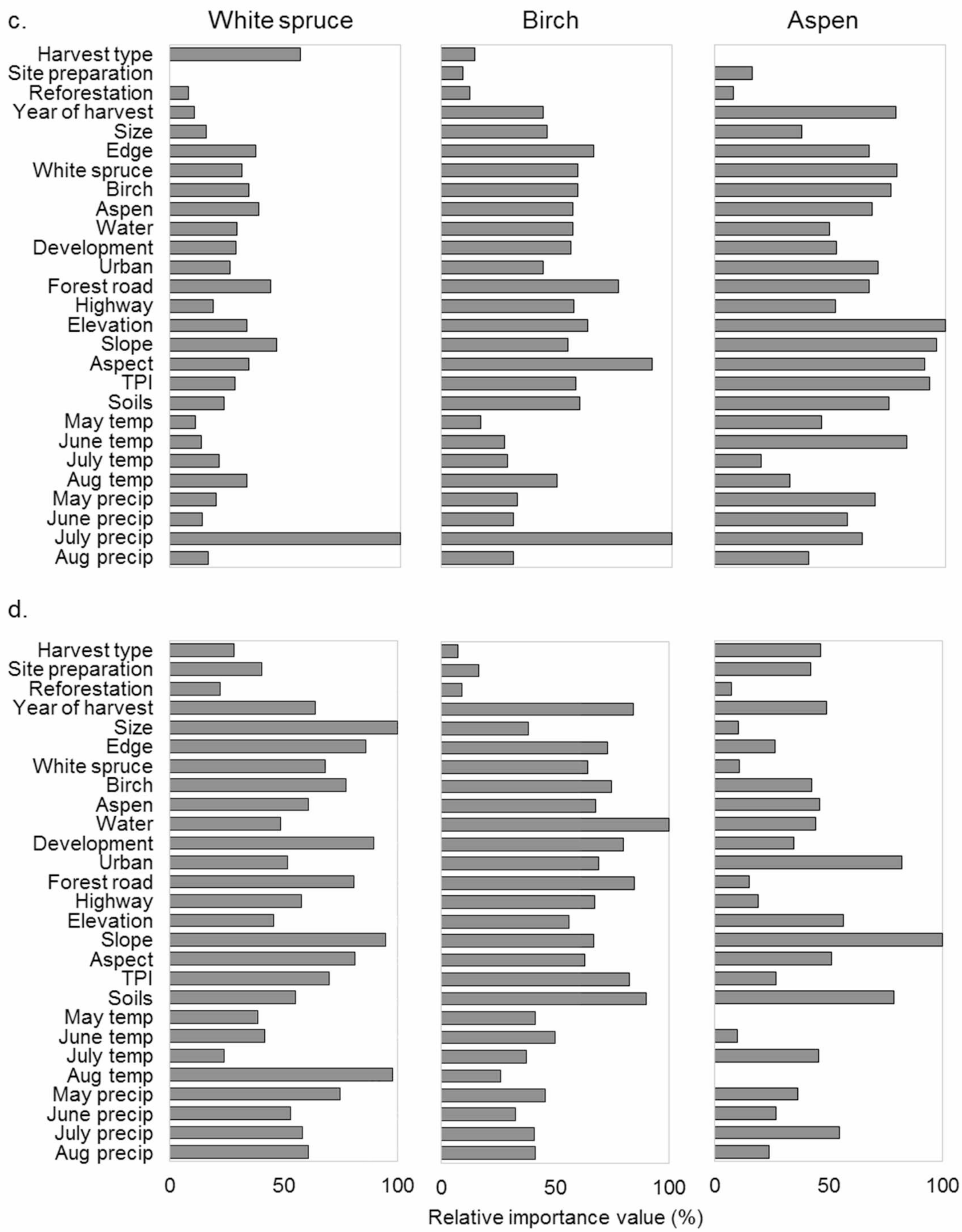

Figure 3.5 cont.

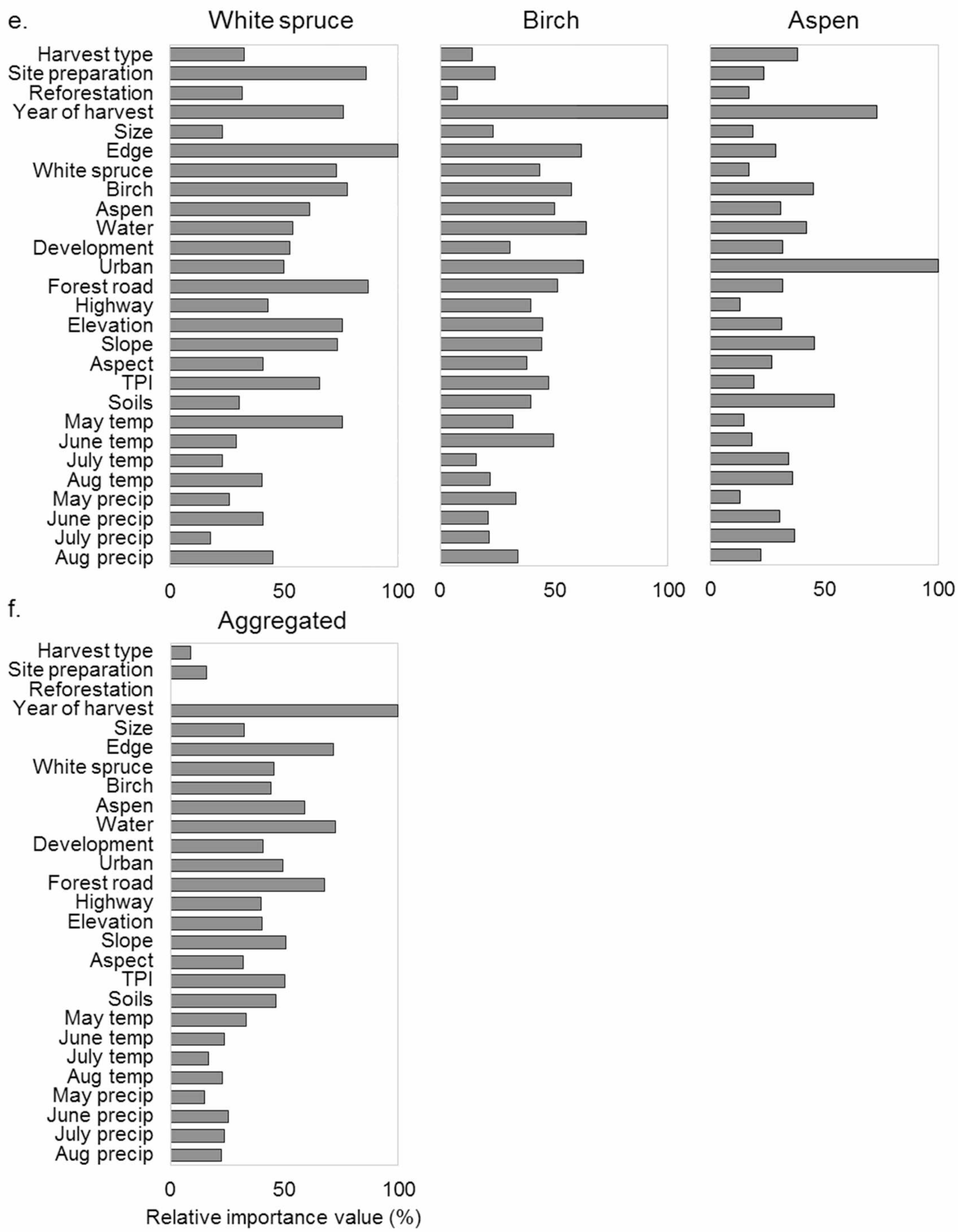

Figure 3.5 cont.

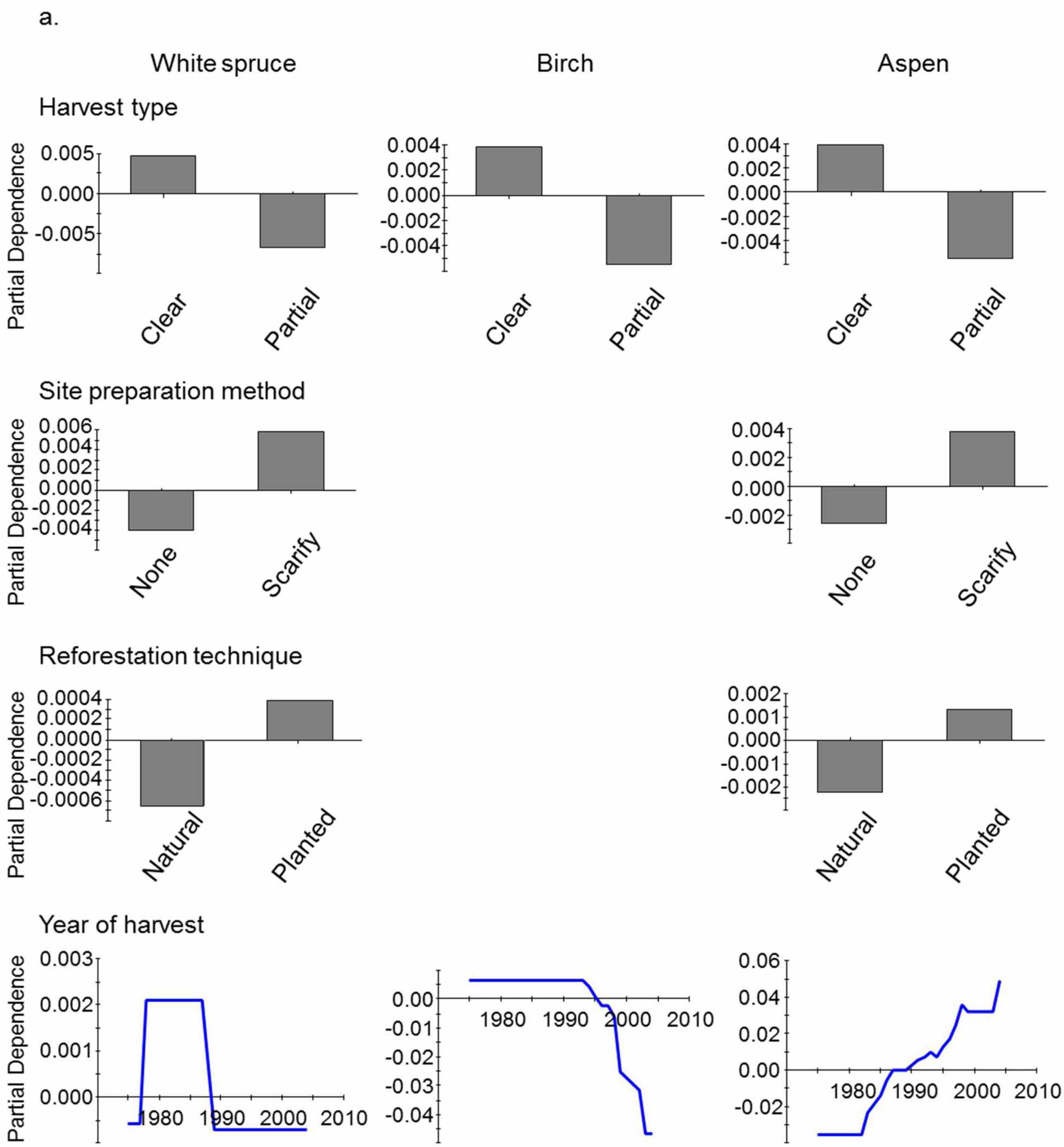

Figure 3.6 Partial dependence plots of harvest type, site preparation method, reforestation technique, and year of harvest for the predictive models of (a) presence/absence of "all size" group, (b) presence/absence of saplings, (c) dominance of "all size" group, (d) dominance of saplings, (e) basal area, and (f) biomass. Partial dependence plots show the relationship between the response and any given predictor by representing the dependence of the response on the predictor variable when all other variables are held at their mean (Hastie et al. 2009). Y-axes are partial dependence value of prediction being 1 (present/high). Empty space means that the TreeNet algorithm found the predictor to be zero importance on the prediction.

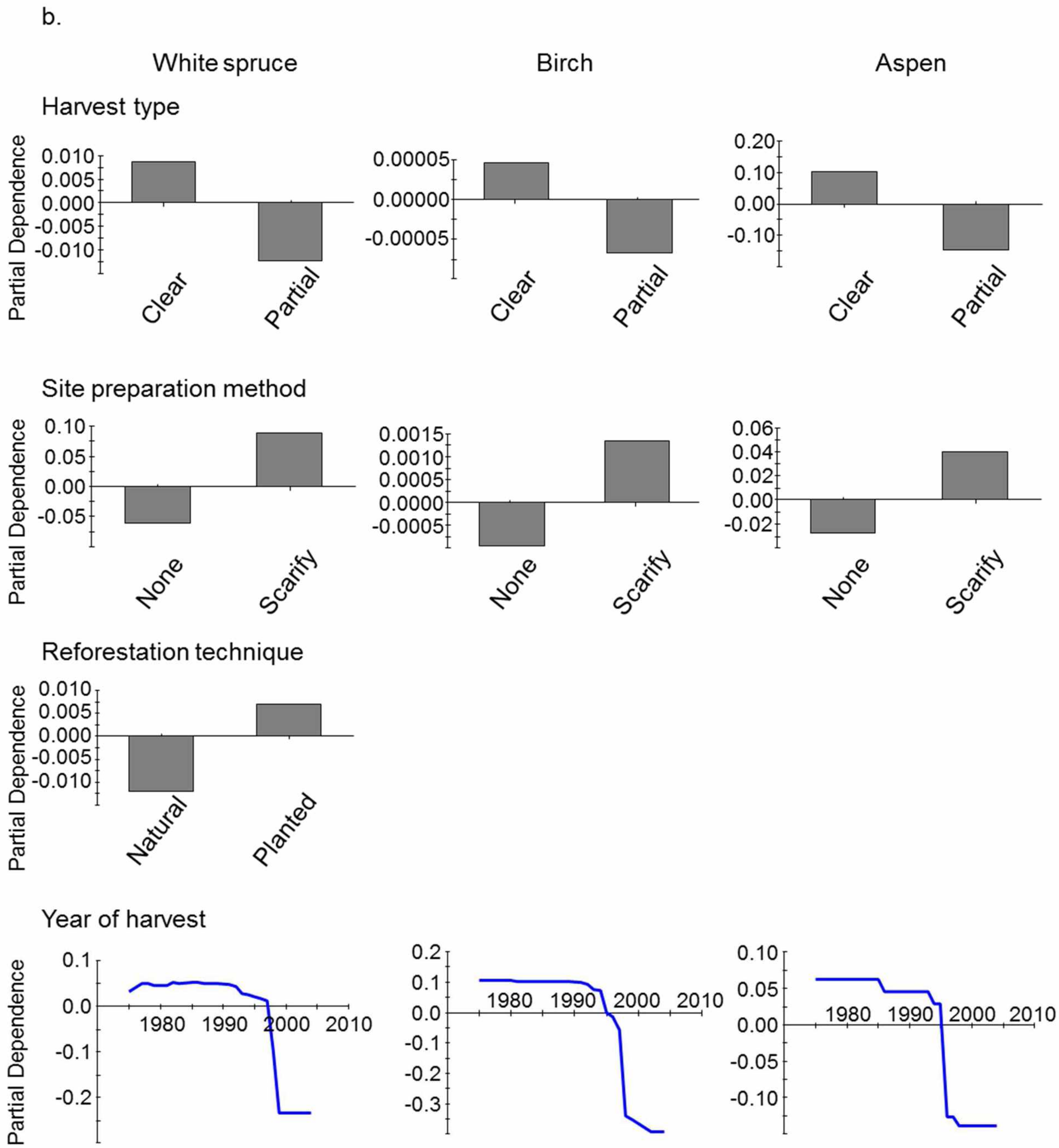

Figure 3.6 cont.

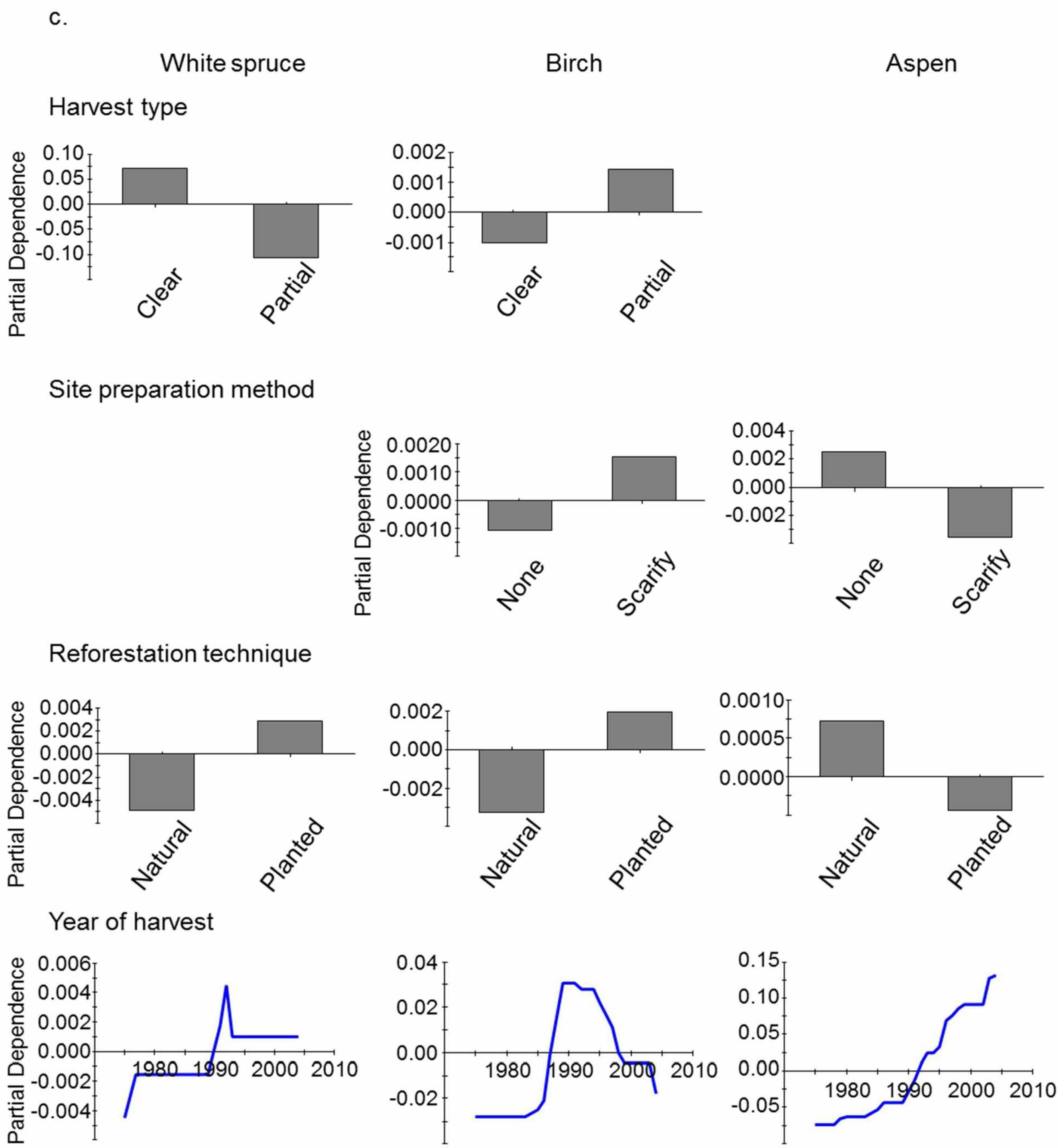

Figure 3.6 cont.

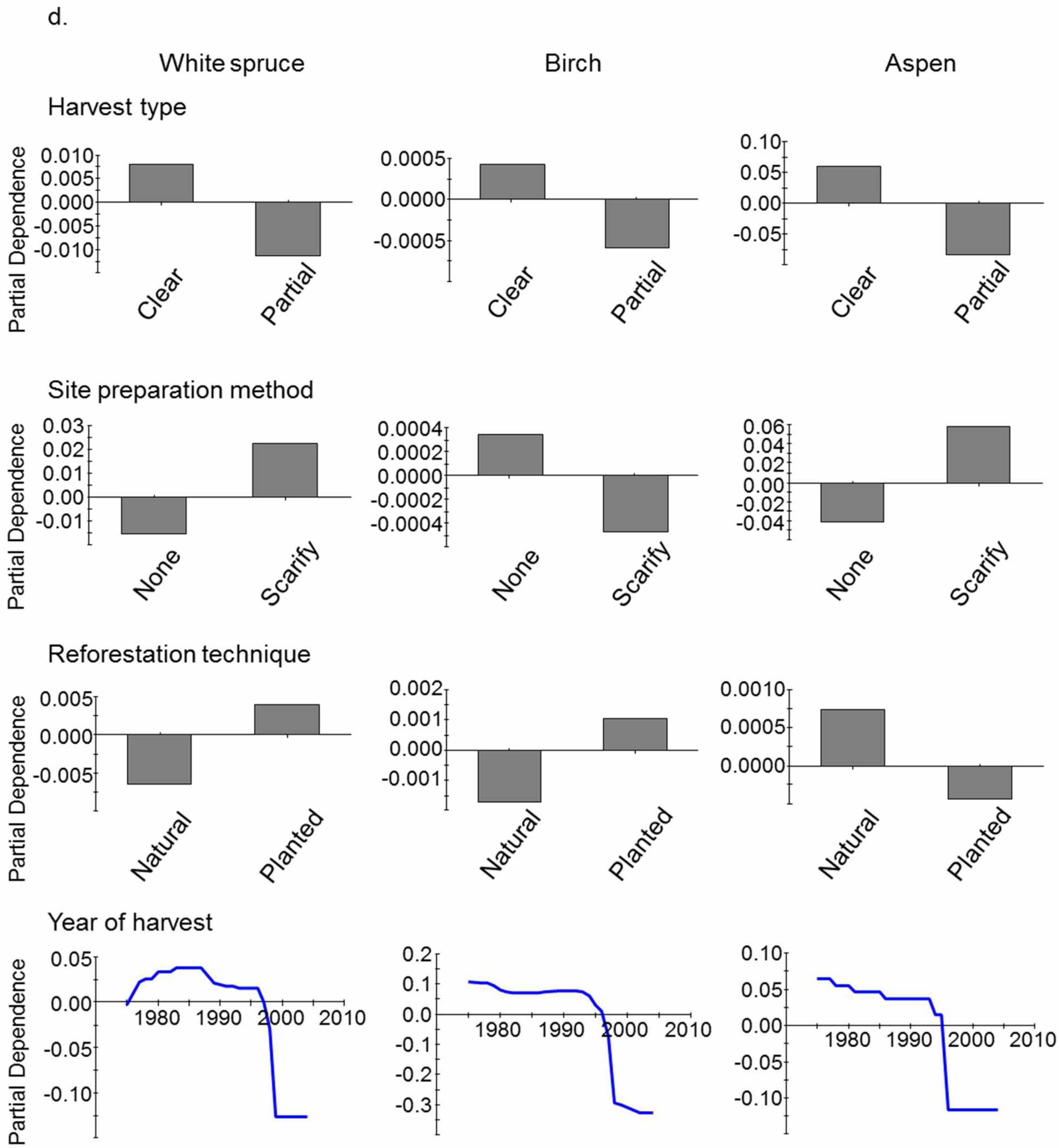

Figure 3.6 cont.

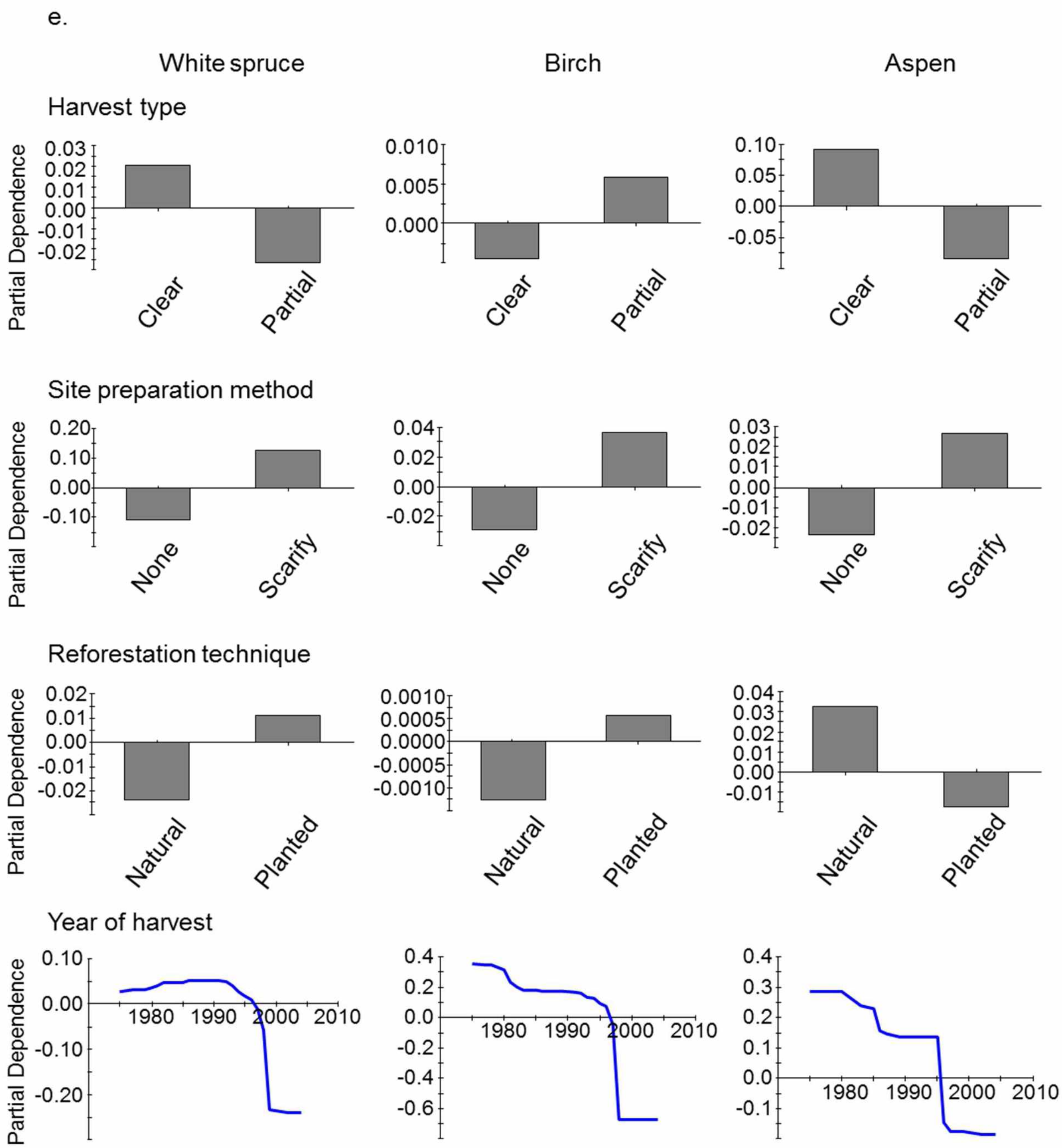

Figure 3.6 cont.

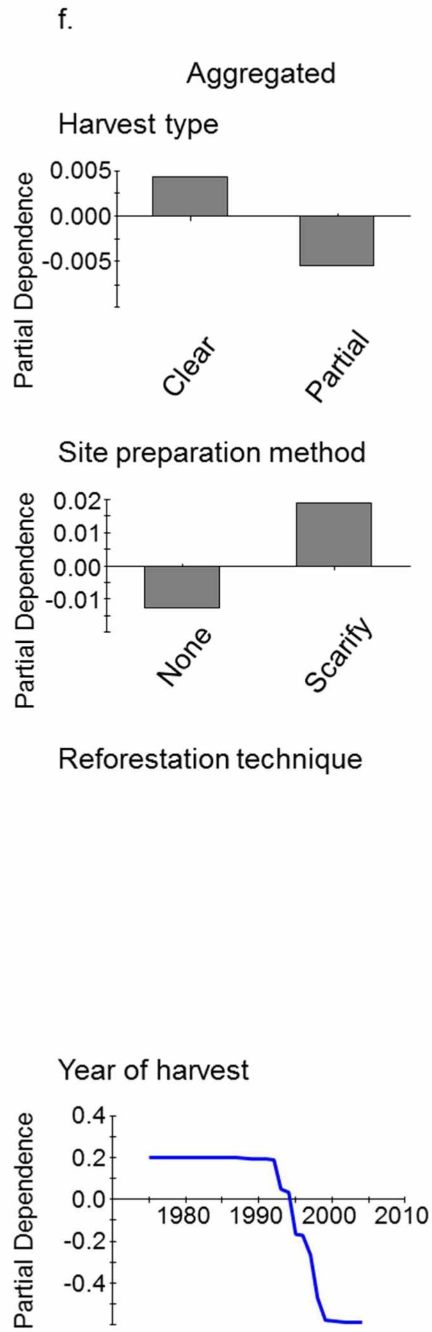

Figure 3.6 cont.

3.9. Tables

Table 3.1. List of sampled harvest units. The location of the units are displayed in Figure 3.1 and the distribution of harvest size was plotted in Figure 3.2b.

Unit	Size (ha)	# plots calculated	# plots sampled	Logged year	Harvest type	Site Preparation	Reforestation
NC-120	10.4	41	41	1975	Partial cut	None	Plant
NC-93	17.9	76	35	1975	Partial cut	None	Natural
NC-190	5.1	22	22	1977	Clearcut	Scarify	Natural
NC-126	5.7	22	22	1978	Partial cut	None	Natural
NC-140-17	2.5	8	8	1979	Clearcut	None	Natural
NC-249	5.0	22	22	1980	Clearcut	Scarify	Natural
NC-362	4.4	15	15	1981	Partial cut	None	Natural
NC-140-38	1.5	7	7	1982	Clearcut	Scarify	Natural
NC-395	5.1	21	21	1983	Clearcut	None	Natural
NC-490	8.4	32	32	1985	Clearcut	None	Natural
NC-556	6.6	26	26	1986	Clearcut	None	Plant
NC-305	3.5	11	11	1987	Partial cut	Scarify	Plant
NC-705	11.0	44	44	1989	Clearcut	Scarify	Plant
NC-454	20.4	87	44	1991	Clearcut	Scarify	Plant
NC-740	1.9	8	8	1991	Clearcut	None	Plant
NC-709	17.2	71	35	1991	Clearcut	Scarify	Plant
NC-842	2.1	7	7	1992	Partial cut	None	Natural
NC-733	30.3	120	44	1992	Clearcut	Scarify	Plant
NC-702	2.0	9	9	1993	Clearcut	None	Plant
NC-747	8.0	31	31	1994	Clearcut	None	Plant
NC-750	9.8	41	41	1995	Clearcut	Scarify	Plant
NC-1085	22.6	94	47	1996	Partial cut	Scarify	Plant
NC-1137	13.5	55	29	1997	Clearcut	None	Plant
NC-927	22.5	90	43	1998	Partial cut	None	Plant
NC-760	3.4	13	13	1998	Partial cut	None	Natural
NC-1129	6.0	22	22	1999	Partial cut	None	Plant
NC-1090	1.4	7	7	1999	Partial cut	None	Natural
NC-1135	11.7	49	49	2002	Partial cut	None	Plant
NC-1116	2.4	9	9	2003	Partial cut	Scarify	Natural
NC-1143	6.7	28	28	2004	Partial cut	None	Natural

Table 3.2 List of response and predictor variables.

Variable	Description	Unit	Data source
Response variables			
Presence/absence	Presence/absence of white spruce, birch, and aspen	category	Field sampling
Species dominance	Species dominance of white spruce, birch, and aspen	category	Field sampling
Basal area	Basal area of white spruce (high ≥ 0.5 m^3, low < 0.5 m^3), birch (high ≥ 1 m^3, low < 1 m^3), and aspen (high ≥ 0 m^3, low < 0 m^3)	category	Field sampling
Biomass	Biomass accumulation (high ≥ 5 t, low < 5 t)	category	Field sampling
Predictor variables			
Harvest type	Harvest type: clearcut/partial cut	category	AKDOFFMD
Site preparation	Ground treatment type: none/mechanical site preparation	category	AKDOFFMD
Reforestation	Reforestation type: natural/planting white spruce seedlings	category	AKDOFFMD
Year	Year since harvest: 10-39	continuous	AKDOFFMD
Size	Size of harvest unit	hectare	AKDOFFMD
Edge	Distance to edge of harvest unit	km	AKDOFFMD
White spruce	Distance to white spruce forest	km	AKDOF vegetation map
Birch	Distance to birch forest	km	AKDOF vegetation map
Aspen	Distance to aspen forest	km	AKDOF vegetation map
Water	Distance to water	km	AKDOF vegetation map
Highway	Distance to highway	km	AKDOF vegetation map
Forest road	Distance to forest road	km	AKDOF vegetation map
Urban	Distance to urban area	km	AKDOF vegetation map
Development	Distance to development (power line, mine etc.)	km	AKDOF vegetation map
Elevation	Elevation	m	GINA DEM
Slope	Slope	degree	GINA DEM
Aspect	Aspect	category	GINA DEM
TPI	Topographic Position Index	continuous	GINA DEM
Soils	Soil subgroup	category	NRCS
May temp	Average temperature of May	°C	SNAP
June temp	Average temperature of June	°C	SNAP
July temp	Average temperature of July	°C	SNAP
Aug temp	Average temperature of August	°C	SNAP

Table 3.2 cont.

Variable	Description	Unit	Data source
May precip	Precipitation sum of May	mm	SNAP
June precip	Precipitation sum of June	mm	SNAP
July precip	Precipitation sum of July	mm	SNAP
Aug precip	Precipitation sum of August	mm	SNAP

Table 3.3 The model performances, including contingency table, specificity (true negative rates), sensitivity (true positive rate), mean accuracy (mean of sensitivity and specificity), and AUC.

		Predictions		Specificity Sensitivity	Mean accuracy	AUC
"All size" group presence/absence		Absent	Present			
Aspen	Absent	491	92	84.22%	0.84	0.92
	Present	22	121	84.62%		
Birch	Absent	176	91	65.92%	0.68	0.74
	Present	138	321	69.93%		
White spruce	Absent	196	74	72.59%	0.73	0.78
	Present	123	333	73.03%		
Saplings presence/absence		Absent	Present			
Aspen	Absent	653	43	93.82%	0.94	0.98
	Present	2	28	93.33%		
Birch	Absent	394	84	82.43%	0.82	0.90
	Present	47	201	81.05%		
White spruce	Absent	422	108	79.62%	0.79	0.88
	Present	44	152	77.55%		
"All size" group dominance		Low	High			
Aspen	Low	580	79	88.01%	0.88	0.95
	High	9	58	86.57%		
Birch	Low	296	84	77.89%	0.78	0.85
	High	78	268	77.46%		
White spruce	Low	377	115	76.63%	0.76	0.83
	High	58	176	75.21%		
Sapling dominance		Low	High			
Aspen	Low	656	44	93.71%	0.94	0.97
	High	2	24	92.31%		
Birch	Low	423	83	83.60%	0.84	0.90
	High	36	184	83.64%		
White spruce	Low	472	111	80.96%	0.81	0.88
	High	27	116	81.12%		
Basal area		Low	High			
Aspen	Low	103	6	94.50%	0.94	0.98
	High	2	32	94.12%		
Birch	Low	194	30	86.61%	0.86	0.93
	High	33	201	85.90%		
White spruce	Low	190	43	81.55%	0.81	0.88
	High	45	177	79.73%		
Biomass		Low	High			
	Low	319	87	78.57%	0.78	0.85
	High	72	261	78.38%		

3.10. Appendices

Appendix 3.1 Forest Management Database for timber sales in the Fairbanks, Kantishna, and Delta management areas of state forest

Column name	Description	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
SALE_NUMBE	Sale number	NC-XXX
SALE_UNIT	Sale unit	NC-XXX-ZZ
ADL_NUMBER	Alaska Division of Land tracking number	Numeric
PURCHASER	Purchaser	Text
Remarks	Notes	Text
DATE_SOLD	Date of sale	MM/DD/YYYY
EXPIRATION	Date of expiration	MM/DD/YYYY
TERM_DATE	Date of termination	MM/DD/YYYY
NEGOTIATED	Type of sale	N; Y; blank
AVG_VAL_SC	Average value of saw component	Dollar
AVG_VAL_FC	Average value of fuelwood component	Dollar
SAW_CCF	Harvest volume of sawlog	ccf
FUEL_CCF	Harvest volume of fuelwood	ccf
SAW_CCF_AC	Harvest volume of sawlog	$ccf \cdot ac^{-1}$
FUEL_CCF_A	Harvest volume of fuelwood	$ccf \cdot ac^{-1}$
SALE_VOL_C	Total Harvest volume of sale	ccf
BIRCH_VOL	Harvest volume of birch	ccf
SP_FUEL_VO	Harvest volume of spruce fuelwood	ccf
ASPEN_VOL	Harvest volume of aspen	ccf
SOLD_FOR	Sale price	Dollar
TOTAL_VALU	Total value of sale	Dollar
IMPROVE_	Development cost (roads etc)	Dollar
SALE_BOND	Bond for performance	Dollar
ROAD_BOND	Bond for project work	Dollar
SALE_NAME	Name of sale	Text

Appendix 3.1 cont.

Column name	Description	Unit/categories
HARVEST_TY	Type of harvest	Clear ROW for birch; Clearcut; Clearcut / Land Use Conversion; Fire salvage; Partial cut/dead&drying spruce only; Partial cut/diameter limit; Partial cut/leave tree birch 50' spacing; River salvage; Road Easement Cutting of 66 ft wide; Salvage; Select cut for aspen; Select cut for aspen and birch; Select cut for birch; Select cut for birch and spruce; Select cut for spruce; Select cut for spruce and cottonwood; Select cut for spruce and optional birch; Select cut for spruce, fuel from ROW; Select cut for spruce, rest ROW; Select for spruce; Select for br, rest in ROW; Select for sp, fuel in ROW; Select for sp, others select for br; Thinning; Blank
Unit	Unit number	Numeric
STATUS	Sale status	Active; Proposed; OTC (on the contract); Reoffer; Terminated; Blank
Acreage	Size of harvest	Acres
Sale_year	Year of sale	Numeric
Species_1	Harvest species	Birch; Spruce; Blank
Management_Block	Management area	Fairbank; Knatishna; Delta
Management_Unit	Management unit	Text
Area_Plan	Management plan	TBAP; TBAP & TVSF; TVSF,TBAP; TVSF/TBAP; Blank
Species_2	Harvest species	Aspen; Birch; Mixed; Spruce; Spruce fuel; Blank
LEGAL_DESCRIPTION	Legal description	Sections, township, range
TOWNSHIP	Township	Text
RANGE	Rage	Text
SECTIONS	Section	Numeric
Bidders		Numeric
SHAPE_Length	Perimeter of polygon	m
SHAPE_Area	Size of polygon (harvest unit)	m^2

Appendix 3.2 Forest Management Database for reforestation in the Fairbanks and Kantishna management areas of state forest

Column	Description	Unit/categories
OBJECTID	id assigned by ArcGIS	Numeric
SHAPE	ArcGIS feature geometry	Long Binary Data
SUBCLASS	class of shape file	POLY (polygon)
SALE_NUMBER	Sale number	NC-XXX
SALE_UNIT	Sale unit	NC-XXX-ZZ
Unit	Unit	ZZ
PLANT_UNIT	Plant unit	NC-XXX-YYa
LOGGED_DATE	Date of harvest	MM/DD/YYYY
SITE_PREP	Method of site preparation	None; blank; Blade; Blacke; Disc trench; Plow; Shear blade
PREP_DATE	Date of site preparation	MM/DD/YYYY
COST_AC_SC	Cost of scarification	Dollar
REGEN_METH	Method of reforestation	Blank; Natural seed; Natural seed + replant; Plant; Plant + replant; Direct seed
YEAR_REGEN	Year of artificial reforestation	Numeric
REGEN_SPEC	Species used for artificial reforestation	Spruce; Lodgepole; S. Larch
REGEN_SP_1	Additional species used for artificial reforestation	Aspen; Larch; Lodgepole; Scotch pine
REGEN_SP_2	Additional species used for artificial reforestation	Larch
SEEDLOT	Seedlot for regeneration species	Text
SEEDLOT2	Seedlot for additional regeneration species	Text
SEEDLOT3	Seedlot for additional regeneration species	Text
CONTRACTOR	Planting contractor	Text
CONTRACT_A	Contract award number for planting contractor	Numeric
COST_PER_T	Cost per tree	Dollar
SPACING	Spacing of planting	Foot
TREES_AC	Number of trees planted per acre	Numeric
PLUG_TYPE	Type of plug	313B; 6-L; R-L; STYRO313B
TREE_AGE	Age of planted planting tree	Numeric
TREE_SOURC	Source of planted tree	K&C; PELTON; PRT; STATE; blank
COLD_STORA	Cold storage of seedlings	N; Y; blank
START_DATE	Start date of artificial regeneration	MM/DD/YYYY
END_DATE	End date of artificial regeneration	MM/DD/YYYY

Appendix 3.2 cont.

Column	Description	Unit/categories
WEATHER	Weather	CLEAR, WARM; COLD; COOL; DRY; GOOD; HOT; OVERCAST; SMOKEY; WET; WET, COOL; blank
TEMP	Temperature	F
REL_HUM	Relative humidity	No records
WIND_SPD	Wind speed	No records
CLOUD_COV	Cloud cover	No records
SOIL_TEMP	Soil temperature	No records
SOIL_MOIS	Soil moisture	No records
REGEN_ACR	Area of regeneration	acre
DATE_SURVEY	Date of regeneration survey	MM/DD/YYYY
NB_of_PLOTS	Number of survey plots	Numeric
STOCK_LOCA	Total percentage stocking (Number of stocked plots/total number of plots)	%
PERC_PL_WS	Percent of planted white spruce	%
PERC_NAT_WS	Percent of natural white spruce	%
PERC_TOT_WS	Percent of total white spruce	%
PERC_NAT_BI	Percent of natural birch	%
PERC_NAT_AS	Percent of natural aspen	%
PERC_NAT_BS	Percent of natural black spruce	%
PERC_NAT_BP	Percnet of natural balsam poplar	%
PERC_PL_PI	Percent of planted lodgepole pine	%
PERC_PL_LA	Percent of planted siberian larch	%
STOCK_NB_TREE	Percent of regeneration standard	%
NB_TOTAL_TREE	Number of total tree	Numeric
NB_PL_WS	Number of planted white spruce	Numeric
NB_NAT_WS	Number of natural white spruce	Numeric
NB_TOT_WS	Number of total white spruce	Numeric
NB_NAT_BI	Number of natural birch	Numeric
NB_NAT_AS	Number of natural aspen	Numeric
NB_NAT_BS	Number of natural black spruce	Numeric
NB_NAT_BP	Number of natural balsam poplar	Numeric
NB_PL_PI	Number of planted lodgepole pine	Numeric
NB_PL_LA	Number of planted siberian larch	Numeric
SHAPE_Length	Perimeter of polygon	m
SHAPE_Area	Area of polygon (reforestation unit)	m^2
OBSERVATION	Notes	Text
STOCK_450	Percent of regeneration standard	%
total_acres	Area of unit	acre

Chapter 4. Continuing Climate Warming Will Result in Failure of Post-Harvest Natural Regeneration across the Landscape in Interior Alaska[1]

4.1. Abstract

Context. In order to manage boreal landscapes sustainably, especially under climate change, it is essential to understand the interaction between environmental and climate factors and post-harvest regeneration across the landscape. Because of limitations on field sampling in Interior Alaska, foresters would benefit from reliable predictions of post-harvest regeneration. Understanding regeneration responses to environmental factors should help identify areas where reforestation will be feasible or might require assistance.

Objectives. This study aims to identify how and to what degree landscape and forest management predictors influence post-harvest regeneration in central boreal Alaska. We build scenarios of plausible future forest conditions under different management treatments and levels of climate change.

Methods. This study was conducted on state forest lands within boreal Alaska. We recorded presence of white spruce, birch, and aspen in 726 plots from 30 harvest units. We built predictions and scenarios of species presence/absence using TreeNet (Stochastic Gradient Boosting) and publicly available climate models.

Results. The post-harvest natural regeneration predictions were highly accurate. Early stage post-harvest regeneration reflects the long-term natural vegetation distribution. The most successful species in post-harvest regeneration following white spruce harvest under climate warming is

[1] Miho Morimoto, Glenn P. Juday, and Falk Huettmann, Continuing climate warming will result in failure of post-harvest natural regeneration across the landscape in Interior Alaska. Prepared for submission to Landscape Ecology.

white spruce. Post-harvest natural regeneration of all the species increases under moderate warming scenarios, but fails in areas with high temperatures and low precipitation under strong warming scenarios.

Conclusions. Forest management in central boreal Alaska needs to be prepared for a climate regime shift. State forest lands cover a broad landscape region with a range in environmental factors. As a result, management practices need to be adjusted specifically to the site.

Keywords: boreal forest, post-harvest regeneration, climate change, scenario, TreeNet (Stochastic Gradient Boosting), landscape factors, forest harvest management

4.2. Introduction

The boreal forest covers about 30% of forest land on the earth (Brandt et al. 2013) and provides various ecological services, such as habitat provision, water cleansing, and climate regulation by carbon sequestration (Pan et al. 2011). The North American boreal forest is still relatively intact ecologically, particularly at the higher latitude regions (Potapov et al. 2008). The North American boreal forest has been described as a stand replacement disturbance-driven ecosystem, of which wildfire is the major disturbance (Chapin et al. 2006a; Foote 1983; Gauthier et al. 2015). As a result, regeneration following the natural disturbances contributes greatly to landscape diversity and to sustaining habitats for a broad range of species. In order to manage boreal landscapes sustainably, it is essential to understand how regeneration responds to timber harvest disturbance to produce patterns of forest ecosystem distribution.

The boreal forest of Alaska is experiencing the effects of several global changes, particularly warming and regional changes related to human activities, such as forest harvest, road building, predator control, and fire suppression (Burton et al. 2010). The Alaska boreal region has experienced a greater amount of warming compared to forest regions in lower latitudes (Chapin et al. 2014). Temperature increases have already begun affecting Interior Alaska boreal forest in many ways, including changing tree growth (increases and declines; Barber et al. 2000; Juday et al. 2015), advancing tree lines into tundra (Wilmking et al. 2004), altered wildfire behavior (Johnstone et al. 2010), and warming or thawing of permafrost (Hinzman et al. 2005). A warmer and drier climate is causing slower growth of mature white spruce due to drought stress in the warm, dry portion of Interior Alaska (Barber et al. 2000; Juday et al. 2015). Although some studies have examined the effects of climate warming on mature white spruce (Barber et al. 2000; Juday et al. 2015), few or no studies have examined the effects of temperature increases on tree regeneration. Although wildland fire has been and continues to be the overwhelmingly dominant form of forest disturbance in boreal Alaska (Gauthier et al. 2015), forest harvest is gradually expanding, particularly for wood biomass (Alaska Division of Forestry 2013; Fresco and Chapin 2009). Forest harvesting could become the most important form of disturbance on the land base dedicated to sustainable forest production in the boreal Alaska. In order to adapt to these changes successfully and to inform the management and regulatory systems to act accordingly, it is essential to recognize the possible response of post-harvest regeneration to these actual or expected changes.

In Interior Alaska, logging occurred in late 19th and early 20th centuries primarily for development of mines and urban areas. The logging in this time period was not management-based and might have altered the current boreal forest landscape significantly in some areas (Roessler 1997). However, reliable records or documentation do not exist to identify the exact location or levels of early logging activities. Operational forest harvest management in central

Interior Alaska began around 1970, primarily for production of sawlogs and salvage of burned or dead/dying trees (Alaska Division of Forestry 2013). However, the scale of forest harvest management has been relatively small throughout this time (less than 2% of timberland on state forest lands has been harvested; Alaska Division of Forestry 2013) due to small demand, limited access, and limited wood product facilities. One result is that forest management in the Interior Alaska boreal forest has relied heavily on natural regeneration. Post-harvest regeneration is influenced by both natural and artificial or management factors, so managers of those forests need a careful analysis of the factors that have led to the success of regeneration in the past.

Both sexual and asexual regeneration make important contributions to boreal tree recruitment following disturbance. Sexual tree regeneration is essentially controlled by the amount of seed produced, seed viability, and distance to the seed source (Purdy et al. 2002). Once seeds encounter a suitable seedbed and become established, seedling success is largely determined by the resources available in its microenvironment and by the severity of competition (Purdy et al. 2002). Seedling microenvironments can be effectively modeled by landscape factors, including climate, topography, and spatial configuration, and by forest management practices. In contrast, asexual tree reproduction does not require seeds but develops from remaining plant parts, and so is less restricted by stochastic environmental conditions compared to sexual reproduction. As a result, asexual reproduction has a higher chance of successful regeneration than sexual reproduction when sufficient vegetative parts remain after disturbance (Zasada 1986). Various forest harvest and reforestation practices create unique environments which can strongly influence the abundance of sexual versus asexual regeneration. A few studies have examined the effects of forest management practices on post-harvest regeneration in Interior Alaska (Wurtz and Zasada 2001; Youngblood and Zasada 1991). However, these previous studies of post-harvest regeneration have accounted only for “artificial” factors but generally not natural factors, including spatial or temporal components.

In Alaska, post-harvest regeneration is required to meet minimum stocking standards established under regulations of the Alaska Forest Resources & Practices Act (FRPA)[2]. The FRPA standard requires 450 seedling-size stems·ac^{-1} (1,112 ha^{-1}) to be present within 7 years in the boreal region, although lower numbers of larger (residual) stems are counted toward meeting the standard (Table 4.1). When more than 10% of harvest area fails to meet the standards, additional regeneration efforts are required (Alaska Division of Forestry 2008). However, there are difficulties in evaluating regeneration success. The road network is not well developed or maintained, and many units are harvested in winter when the rivers and bogs are frozen and thus drivable for operations only seasonally. Because of the lack or bad condition of all-season roads, comprehensive field sampling of post-harvest regeneration in Interior Alaska is expensive and time consuming. In addition, a majority of forest management staff and funding is used for fire management in Interior Alaska in the summer, which leaves few resources available for regeneration surveys. As a result, predictions of post-harvest tree regeneration that reliably identify regeneration success would save a large amount of time and money, and allow a pro-active and precautionary management scheme in times of climate change.

Methods such as boosted regression trees allow the prediction of post-harvest regeneration accurately with a limited amount of field observations in a multivariate fashion with a large number of predicting factors (Friedman et al. 2000). In addition, machine learning

[2]Alaska Forest Resources and Practices Regulations (11 AAC 95) implement and interpret AS 41.17 (Forest Resources and Practices Act (FRPA)). The requirement of regeneration survey is mentioned in section 385 of the regulations. Booklets of FRPA and the regulations are available at http://forestry.alaska.gov/forestpractices.

methods can contribute to a better and more complete understanding of the complex processes of post-harvest regeneration, particularly because of their ability to apply a large and realistic number of ecosystem predictors that affect regeneration. Over 100 machine learning algorithms exist; boosting and bagging appear to be among high-performing algorithms that achieve such goals. TreeNet is a specific and fine-tuned algorithm of the group of 'stochastic gradient boosting' algorithms, which creates many weak learners with improvements using the residuals from the previous trees creating a strong learner that is optimized (Friedman et al. 2000). Stochastic gradient boosting in general improves upon gradient boosting by drawing random subsets at each iteration (Hastie et al. 2009).

The objective of this study was to identify how and to what degree landscape and forest management predictive factors influence post-harvest regeneration in central Interior Alaska boreal forest using latest science-based methods, based on predictions (Breiman 2001). Here we use 27 predictors for a TreeNet analysis, most of which are publicly available. We then apply these factors to build scenarios of plausible future forest conditions under different management treatments and levels of climate change.

4.3. Methods

4.3.1. Study area

This study was conducted within the Fairbanks and Kantishna Management Areas of the Tanana Valley State Forest and state forest classified land ("state forest lands"; Figure 4.1). The study area is located within the boreal Alaska which is primarily composed of white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.)), Alaska birch (*Betula neoalaskana* Sarg.), quaking aspen (*Populus tremuloides* Michx.), with minor amounts of balsam poplar (*Populus balsamifera*), and tamarack (*Larix laricina*; Labau and van Hees 1990). Soils are mostly silt loams formed from loess parent material (Ping et al. 2006). Elevations range from 100 m to 600 m. The climate of the study area is strongly continental and varies substantially according to factors such as elevation and aspect (Shulski and Wendler 2007).

The principal long-term NWS First Order station for the study area is Fairbanks International Airport (1948-present; 133 m). The Fairbanks Airport climate record is a single point record taken on a grass surface near the runway (not forest). Due to the general lack of climate measurements in Alaska, the Airport climate record is traditionally used as one reference point in a number of analyses of climate trends and forest growth studies (Juday and Alix 2012; McGuire et al. 2010; Wilmking et al. 2004). Mean annual temperature at Fairbanks Airport is -2 °C and annual precipitation of 270 mm, with extreme temperatures ranging from -50 °C to 35 °C. The period between freezing temperatures in the early 21st century is approximately 123 days at Fairbanks, an increase from 85 days in the early 20th century (Wendler and Shulski 2009). However, climate in the region varies substantially according to factors such as elevation and aspect (Shulski and Wendler 2007). Temperature inversion is a dominating factor that creates great temperature variability by elevation, especially in winter (Shulski and Wendler 2007). Geographically continuous, locally relevant climate data have been generated by downscaled modeled climate data for the study area (SNAP 2015).

4.3.2. Silvicultural systems

The two primary regeneration harvest methods used on state forest lands are the clearcutting and partial cutting systems (Alaska Division of Forestry 2013). Both of these systems have been utilized for green wood and post-fire salvage harvests. The clearcut system as utilized in Interior Alaska has ranged from a conventional clearcut, to a clearcut with reserves (The Society of American Foresters 1994). Partial cuts typically involved one of two types: the removal of a single species from mixed stands, either white spruce or birch, or an intermediate harvest with diameter limits. Regardless of the harvest system, whole tree harvesting was solely utilized during the period of the analysis (B. Young personal communication).

In order to enhance seedbed quality for white spruce germination, mechanized site preparation is often applied following harvest (Youngblood et al. 2011; Youngblood and Zasada 1991). The primary site preparation treatments used in Interior Alaska have involved scarifying, using either the edge of a dozer blade or a disk trencher. Many harvest units relied on natural regeneration as the primary regeneration method, while others utilized artificial reforestation techniques for white spruce. In the Fairbanks and Kantishna area of state forest lands, the two most common artificial regeneration techniques utilized included direct seeding or the planting of container stock. For both of the methods, seeds were typically collected from local sources (Alaska Division of Forestry 2000).

4.3.3. Sampling, predicting, and building scenarios of post-harvest regeneration

We obtained the Forest Management Database of state forest lands, maintained by the Alaska Department of Natural Resources, Division of Forestry (Alaska Division of Forestry 2013). The AKDOF database is a GIS-based collection of records of the location and type of all management activities that has occurred on state forest lands within the Fairbanks and Kantishna area (see Figure 4.1b) since 1972, archived in Microsoft Access (Appendices A and B). The database, at the time it was accessed for this study (2013), contained records for 966 units harvested from 1972 until 2012. Harvest units varied in size from ~ 1 to a few hundred ha. The size distribution of the 966 harvest units was positively skewed, with a median of 4.66 ha and a mean of 10.89 ha. During the period 1972 – 2012 (the period for which forest harvest data exist), a natural regeneration harvest treatment was applied on 7,647 ha out of the total 10,973 ha harvested in the Tanana Valley State Forest and state forest classified land (Alaska Division of Forestry 2013; Morimoto 2016).

In this study, we chose historical harvest units that were either clearcut or partial cut in white spruce and mixed spruce-hardwood types. We excluded units that were partial cut for birch, or were salvage logged following fire (collectively 261 out of 966 units). The site preparation treatments used in this study involved mechanical scarification using either a bulldozer blade or a disk trencher. We did not classify the methods used for scarification. We also included only natural regeneration and planting of white spruce seedlings from container stock as the reforestation methods because they were the predominant techniques used. As a result, we analyzed two types of harvest (clearcut/partial cut), two types of ground treatment (scarified/control), and two types of reforestation (planting spruce/natural regeneration). All harvest units that we sampled were harvested once between 1975 and 2004 and were not burned following the harvest.

In order to obtain data to build prediction models and scenarios, we sampled 30 harvest units, evenly distributed by management practices, the year of harvest, size of harvest units, and the geographical location across the study area ("sample units"; Table 4.2, Figure 4.1b). To build future regeneration scenarios, we created "scenario units" in the study area (Figure 4.1b). Since our focus was on regeneration following white spruce harvest, we established scenario units in current white spruce sawlog stands on state forest lands based on a land cover map prepared by AKDOF using ArcGIS version 10.2 (ESRI 2013). When the white spruce sawlog stand was larger than 50 ha, we split the polygon into multiple scenario units in ArcGIS because most historical harvest units (98%) are smaller than 50 ha and the predictive models were built using empirical data from sample units ranging from 1.4 ha to 30.3 ha in size (Table 4.2).

For ground sampling and model building, we adopted a 1.69 m radius circular plot, which is the same plot size (1/450 ac or 8.99 m^2) as the AKDOF regeneration survey used to determine compliance with the reforestation requirement of FRPA (Alaska Division of Forestry 2008). Thus, the presence of one tree stem per plot when expanded to the landscape scale would meet the FRPA reforestation standard (Table 4.1). The sampling intensity was determined based on a preliminary test of sampling efficiency using a censused population of white spruce in the study region (Juday 2012). Based on this analysis, we chose four 1.69 m radius circular plots ha^{-1} as our sampling intensity. To determine the placement of both actually sampled and scenario plots, we created a virtual 50 m × 50 m grid with points at the center of each cell over the entire study area using the fishnet tool in ArcGIS (Figure 4.2). The number of plots required according to the protocol varied between 7 and 120, due to both the size and geographic configuration of the harvest units (Table 4.2). Because we prioritized sampling a large number of harvest units over intensive sampling in a single harvest unit to cover a greater area and more replications of management practices and years, the sampling intensity was truncated in the larger harvest units to less than 50 plots. To truncate we sampled every other or every third plot when the protocol initially required more than 50 or 100 plots, respectively. In units where only every other plot and every third plot was sampled, sampled plots were selected to evenly distribute them starting from the first plot (Figure 4.2). The coordinates of the plots (+/- 1m) were exported to Trimble Pro XT GPS unit (Trimble Navigation, California) and were used to navigate to the sample plot centers.

4.3.4. Data collection and preparation

4.3.4.1. Trees and tall shrubs

Field sampling was conducted during the summers of 2013 and 2014. Within each plot, we recorded presence of naturally regenerated white spruce, birch, and aspen post-harvest stems. Planted white spruce seedlings and residual stems originating before harvest are not included in this analysis. We distinguished planted white spruce seedlings from seedlings of natural origin based on planting records, age, and growth pattern in early age, and alignment in planted rows with other white spruce stems when visible. Residual stems were distinguished from post-harvest regeneration based on estimated age of the tree.

4.3.4.2. Predictors

We obtained the values of field predictors at the center of a 50 m × 50 m lattice grid (Figure 4.2). All the predictors are listed in Table 4.3. Type and year of harvest, site preparation method, reforestation technique, and size of harvest unit were obtained from the AKDOF Forest Management Database (Alaska Division of Forestry 2013). Elevation (m), aspect, slope (degree), and topographic position index (TPI; Jenness et al. 2013) were obtained from a 5-m resolution digital elevation model (DEM) created by Geographic Information Network of Alaska (GINA) in ArcGIS. The DEM has 90% probability of 3-meter vertical accuracy, and 90% probability of 12.2-meter horizontal accuracy. The GIS data and metadata for the DEM are available at http://ifsar.gina.alaska.edu/. Aspect was transformed using the following equation;

$$(1 - \cos(2\pi \times \text{aspect}/360))/2$$

where aspect is measured in degrees. Slope was considered flat when it was less than 5 degrees. TPI is an index of topographic position which was calculated using a Land Facet Corridor Designer, v. 1.2.884 tool (Jenness et al. 2013) in ArcGIS.

We used the AKDOF land cover map (Hanson 2013) to calculate distances (m) from each plot within a harvest unit to various features with the "Generate Near Table" tool in ArcGIS. The features include mapped stand polygons of white spruce forest, birch forest, aspen forest, water features, highways, forest roads, developed area, and urban area. The land cover map was created prior to this study by AKDOF staff based on field measurements and aerial photo interpretations (Hanson 2013). In some cases the sample unit might have had a white spruce seed source stand closer than indicated on the current land cover layer because of additional harvesting in the landscape after the sample unit was harvested. In such cases, the landscape harvested unit nearest to the sample unit was considered as a white spruce forest if it was harvested eight years or more after the harvest of the sample unit. We used eight years because white spruce most likely produces medium to large seed crop every seven years (Roland et al. 2014). The soil type predictor was derived from USDA Natural Resources Conservation Service soil maps. The soil maps are available online at http://websoilsurvey.nrcs.usda.gov/ and the details of the survey are available in National soil survey handbook (U.S. Department of Agriculture Natural Resources Conservation Service 2015). We assigned soil subgroups to each plot in the sample units and the scenario units using ArcGIS.

Downscaled historical and predicted future average monthly temperature and monthly precipitation of 1975-2009 and 2015-2034, respectively, were obtained from the Scenarios Network for Alaska + Arctic Planning (http://www.snap.uaf.edu/data.php). The resolution of the downscaled climate data is square pixels of 771 m. We used predicted future climate derived from General Circulation Model version 3.1 - t47 (Canadian Center for Climate Modeling and Analysis; Flato et al. 2000). We used climate data of the growing season (May-August) because tree growth is greatly affected by climate variables during summer months (Beck et al. 2011; Lloyd et al. 2013; Wilmking et al. 2004). We averaged mean monthly temperatures and total monthly precipitation of twenty years post-harvest, which is the most critical time period for tree regeneration (Van Cleve et al. 1996).

4.3.5. Predictions and scenarios

4.3.5.1. Building predictive models and evaluating predictive accuracies

We used the TreeNet algorithm implemented in the Salford Predictive Modeler version 7 (Salford Systems 2013a). Our prediction was based on a binary outcome of presence or absence of white spruce, birch, and aspen for each TreeNet classification run. If the relative index of occurrence in a given run was rated as less than (greater than) 0.5 the species was classified as absent (present). To construct the decision trees used by TreeNet, a 'balanced' option which corrects unequal class sizes was selected (Salford Systems 2013b). We decided to grow 1,000 trees but the actual number of trees used was optimized by the program for each predictive model (Salford Systems 2013b). For validation purposes, we used the testing method of cross-validation with a randomly selected 10% sample. All other options were set at default values (Salford Systems 2013b). The model performances were evaluated by applying the predictive model to the complete data set, and obtaining average accuracy and area under the receiver operating characteristic (ROC) curve (AUC). The average accuracy is a mean of classification accuracies of each class. The ROC curve demonstrates the performance of a binary classifier system by plotting the true positive rate against the false positive rate at different discrimination thresholds (Pearce and Ferrier 2000). A perfect model will score an AUC of 1, while random guessing will score an AUC of around 0.5 (Metz 1978).

In order to examine the relationship between predictors and species presence/absence, we evaluated the relative variable importance and partial dependence plots. The importance value can be used as a metric of its relevance (Hastie et al. 2009). The importance value of a given predictor is determined by averaging the number of times the predictor is selected as a tree node over all trees and squaring improvements in error rate resulting from these nodes (Hastie et al. 2009). A relative importance value of 100 is assigned to the most important predictor, and relatively scaled values are assigned to other predictors based on the most important predictor. Partial dependence plots show the trend of response in relation to any given predictor by representing the dependence of the response on the predictor variable when all other variables are held at their mean (Hastie et al. 2009).

4.3.5.2. Tree regeneration scenarios 38 years after harvest under a half-century of climate change

We built scenarios of tree regeneration 38 years (the maximum regeneration period in our empirical data) after harvest under three IPCC climate scenarios, including B1, A1B, and A2 (IPCC 2007), and projected historical climates (SNAP 2015). All the scenario units under each climate scenario were assumed to receive the same combination of management practices. We assigned all the eight combinations of management practices for each of the climate scenarios (= two harvest types, two site preparation, and two reforestation), resulting in 32 different scenarios for each of the three tree species (total 96 scenarios; Appendix 4.1). For the historical climate scenario, we assumed that all the scenario units were harvested in 1975. In order to evaluate post-harvest regeneration in the foreseeable future under various climate and management scenarios across study area, we assumed all the scenario units were harvested in 2015, resulting in projections of post-harvest regeneration in 2053. The presence/absence of natural regeneration of white spruce, birch, and aspen 38 years after harvest in the scenario units were predicted under future and historical climate and management scenarios, using the predictive models built earlier (section *4.3.5.1*). We calculated the percent of plots that contain regeneration of each species for each scenario.

Finally, in order to identify areas which face a higher prediction of losing tree regeneration with a projected strong temperature increase, we compared predicted presence/absence (1/0) of each species in each pixel between historical vs. A2 climate scenario. For this analysis, we specified conditions that reflect realistic management assumptions and a plausible level of ultimate temperature increase (A2 scenario), even if it may be realized later than the reference dates for a lower range scenario (e.g. B1). First, we used the management scenario of clearcutting, no site preparation, and natural regeneration. We excluded plots that were predicted to have no regeneration under historical climate. Finally, we ran the TreeNet algorithm to identify the relationship between the loss of tree regeneration and the landscape and forest management predictors. For this analysis, we excluded plots that were predicted to have regeneration under the A2 scenario but not under historical climate (white spruce 2.6%; birch 3.1%; aspen 0.06%) from this analysis.

4.4. Results

4.4.1. Model Performance

Predictive accuracy (presence versus absence of a given species at the plot level) and AUC were both fairly high for predictions of all species (Table 4.4). The model performance is highest for aspen and lowest for birch (Table 4.4). Although the sampled empirical presence/absence classes that calibrated the model are imbalanced, especially for aspen, the predictive accuracies for presence and absence of all the species are nearly equal. As a result, we perceive the scenarios and the prediction outcomes as robust, reliable, and useful for inference.

4.4.2. Variable Importance and Relationships to Species Presence

4.4.2.1. Topography

Topography was one of the most important predictors of species presence for regeneration of all three tree species, but especially so for aspen (Figure 4.3a-c). All four topographic predictors, including elevation, slope, aspect, and topographic position index, were in the top 12 important predictors for aspen, while only elevation and slope were in the top 12 predictors for white spruce and birch (Figure 4.3a-c). Aspen (post-harvest regeneration) tends to occur between 170-300 meters elevation, and on gentle south facing slopes to ridge tops (Figure 4.4a-d). White spruce regeneration tends to occur at elevations higher than 200 m, and on flat to gentle south facing middle slope positions (Figure 4.4a-d). Birch regeneration occurs primarily on flat to gentle northerly facing slopes, and on lower slope positions, such as valley bottoms (Figure 4.4a-d).

4.4.2.2. Distances to various forest types and water

Distances to white spruce, birch, and/or aspen forest type polygons are highly important in the prediction of white spruce and aspen presence in post-harvest regeneration, but not very important for birch (Figure 4.3a-c). White spruce is more likely to be present in plots 25-150 m from birch forest than other distances from birch stands (Figure 4.4e). Aspen presence is greater in plots closer to aspen forest, but aspen is not likely to occur in plots that are within 50 m of white spruce forest (Figure 4.4f-g). Distance to water is one of the most important predictors for white spruce presence/absence, and is the most important predictor for birch (Figure 4.3a-b). White spruce and birch are both less likely to be present in plots closer to water (within 500 m and within 200 m, respectively; Figure 4.4h).

4.4.2.3. Distances to artificial features

Distances to development, urban area, highways, and forest roads have great effects on presence of all three tree species in post-harvest regeneration (Figure 4.3a-c). Overall, distance to urban area contributes the most among those four predictors (Figure 4.3a-c). All species are more likely to be present in plots closer to urban areas than more distant (Figure 4.4i). White spruce presence shows similar trends in response to distance to development and in distance to urban area. White spruce tends to be present within 1,500-2,500 m of urban area and of development (Figure 4.4i-j). In contrast, birch presence in relation to distance to development and urban area shows different trends (Figure 4.4i-j). Birch presence decreases with distance to urban area, while birch presence is likely to be greatest when 10,000 m or more away from development (Figure 4.4i-j). Aspen presence is relatively high within the area up to 10,000 m from urban area (Figure 4.4i). Distance from forest road is relatively important for all species, but distance from highway is much less important (Figure 4.3a-c). Birch and aspen are both predicted to have exceptionally high occurrence when distance to forest road approaches zero (Figure 4.4k).

4.4.2.4. Soil type

Soil type is one of the most important predictors for presence/absence of all species, but particularly for aspen (Figure 4.3a-c). Aspen is most likely to be present on Aquic Haplocryepts, Typic Haplocryepts, and Typic Dystrocryepts. White spruce is more likely to occur on Typic Haplocryepts. On the other hand, birch presence is predicted to be greater on Typic Aquiturbels, Typic Cryofluvents, Typic Dystrocryepts, and Typic Haplocryepts than the other soil types. All of the species show a preference for Typic Haplocryepts and none of the species show dependence on Aquic Cryofluvents (cold soil type).

4.4.2.5. Climate

Some specific months of temperature and precipitation, within the range of values typical of this study area, contribute great importance to species presence predictions in post-harvest regeneration (Figure 4.3a-c). White spruce tends to occur where May precipitation is low, and July precipitation is moderate (50-70 mm; Figure 4.4m-n). Cool temperatures in May and August contribute to white spruce presence (Figure 4.4p). August temperature and precipitation are one of the most important predictors for the occurrence of birch (Figure 4.3b). The occurrence of birch is more likely when August temperature is lower than 13.8 °C and August precipitation is greater than 50 mm (Figure 4.4o-p). May precipitation is the most important predictor for aspen presence (Figure 4.3c). The presence of aspen is higher in plots with precipitation of less than 20 mm in May, while aspen occurrence is more likely when June precipitation is higher than 42 mm (Figure 4.4m, o).

4.4.2.6. Management practices

The specific management practices we evaluated (see Figure 4.3) are the least important predictor for the presence of all three species, particularly for birch (Figure 4.3a-c). Year since harvest is the most important predictor for white spruce presence (Figure 4.3a). White spruce is less likely to be present within 15 years of harvest compared to later.

4.4.2.7. Post-Harvest Forest Regeneration Scenarios

We built post-harvest regeneration scenarios to examine the response of tree regeneration to changing climate and forest harvest practices. Tree regeneration varies greatly among the climate scenarios (Figure 4.5a-c). The proportion of scenario plots that contain regeneration is highest under the B1 (less warming) scenario and lowest under the A2 (more warming) scenario for all species (Figure 4.5a-c). The proportion of scenario plots containing regeneration for all species under the B1 scenario is higher than the historical climate (Figure 4.5a-c). Similarly, under the A1B scenario more plots contain white spruce and aspen regeneration than under the historical climate (Figure 4.5a, c). The predicted occurrence of regeneration is highest for white spruce and lowest for aspen, regardless of scenarios (Figure 4.5a-c). Along the rivers the predicted attainment of the state stocking standard, assuming regeneration occurs by only one species, is generally nonexistent or very low for all three modeled species under the all climates (historical and scenario climates; excludes balsam poplar; Figure 4.6a-d).

White spruce, birch, and aspen all experience post-harvest natural regeneration failure under the A2 scenario when compared to historical climate on sites that are currently low favorability environments for each species. Compared to the historical climate, under the A2 scenario white spruce regeneration falls below the 0.5 threshold (= absent) in extensive areas of lower elevation and lower slope positions, near water, and on northerly aspects (Figure 4.6a-b). Areas with lower May and June precipitation and farther from remaining unharvested white spruce forest also experience regeneration failure. Birch experiences regeneration failure on the upper portion of steep, south slopes at lower elevations, areas farther from remaining birch forest, and areas with low July and August precipitation and high May and August temperatures (Figure 4.6c-d). Finally, aspen regeneration fails at lower elevation and slope positions, areas further from aspen forest, and areas with low July and August precipitation but high June and August temperatures.

Scenario regeneration of all species tends to meet the FRPA standard with higher probabilities in clearcuts compared to partial cuts, especially birch under more severe climate change (e.g. birch regeneration under A2 scenario; Figure 4.5). Site preparation is associated with greater success in meeting the FRPA standard for white spruce and aspen regeneration in all climate scenarios (Figure 4.5). Planting white spruce seedlings appears to make no difference to success in meeting the standard for any species in any of the climate scenarios (Figure 4.5).

4.5. Discussion

4.5.1. Model Performance

Our dataset and analysis successfully predicted presence/absence of white spruce, birch, and aspen post-harvest natural regeneration with an acknowledged high accuracy (Table 4.4) based on simple physical and management factors (Table 4.3). This is the first study analyzing the relationship between post-harvest regeneration and environmental factors. The highly accurate predictions generated can guide foresters in understanding likely post-harvest regeneration, particularly in identifying areas where greater reforestation assistance may be required. As a general proposition, regeneration prediction is acknowledged to be an important tool to adapt to changing climate and forest management goals (Miina et al. 2006).

In many studies of tree reproduction following forest disturbance, prediction outcome and accuracy are influenced by scales, including extent, grain, and resolution sizes (Dungan et al. 2002). We determined the extent based on sampled data availability (Figure 4.1). For grain size, we used 1.69 m radius circular plot (1/450 acre), because it matched the AKDOF regeneration survey, which is supposed to be conducted within seven years post-harvest (Alaska Division of Forestry 2008). Generally, the size of vegetation sample plot is influenced by the size of the vegetation (Stohlgren et al. 1995). Tree size in our study varied greatly between harvest units because the period between harvest and our sampling varied from 10 to 40 years. Thus, in future studies of Alaska tree regeneration in post-harvest succession, it might be desirable to use various plot sizes to account for the tree size difference among harvest units (Stohlgren et al. 1995).

We used a resolution of 50 m × 50 m based on our study objectives and sampling feasibility. If spatial variance is large, a greater number of plots, or finer resolution, become necessary for equivalent model fit and resulting predictive model accuracy. Tree establishment and early growth are largely determined by smaller scale processes, such as microenvironment and distance from seed source (Cater and Chapin 2000). If the resolution becomes too large, the environmental factors would be averaged and would not detect variation within the grid well. On the other hand, the smaller the resolution becomes, the more field sampling is necessary. Therefore, it is essential to find an optimized resolution that is able to provide useful information for post-harvest regeneration management but is feasible to sample. We believe that the resolution we applied in this study was optimized for our study objectives and sampling feasibility.

4.5.2. Variables that Influence Post-Harvest Regeneration

The TreeNet algorithm is not only capable of producing highly accurate predictions, but it also can rank the contribution of variables and identify trends between predictors and species occurrences (Breiman 2001). Variable importance and partial dependence plots assist in the interpretation of the models and also make predictions transparent (Figure 4.3and 4.4). We found that topographic variables made a great contribution to post-harvest regeneration predictions, but management practices had hardly any influence (Figure 4.3a-c). Post-harvest regeneration on southerly aspects is more likely to contain white spruce and aspen, while northerly aspects support high occurrence of birch. White spruce, birch, and aspen regeneration show a gradient in occurrence across slope positions. Aspen tends to occur on steeper and higher slope positions, white spruce occurs on flat to gentle middle slopes, and birch occurs on flat to gentle, but lower slope positions.

In Interior Alaska, soil temperature can vary greatly among different topographic positions, even where the variance of air temperature is small (Hinzman et al. 2006). Slope aspect influences soil temperature substantially in high latitudes due to the low sun angle (Hinzman et al. 2006; Rosenberg 1983). In Interior Alaska, north-facing slopes receive a much smaller amount of solar radiation than south-facing slopes, and soils on these aspects are cold or underlain by permafrost (Shulski and Wendler 2007). On these cold or permafrost-dominated soils nutrient element turnover rate is very slow and black spruce forest occurs, or birch if the active layer is deep enough (Chapin et al. 2006a). South-facing slopes, on the other hand, receive more sunlight which results in warm, permafrost free soils (Shulski and Wendler 2007). Steep south slopes are closer to perpendicular to direct radiation due to the low sun angle, which results in more soil heating. Higher topographic positions such as ridge tops and middle slopes receive more sunlight and drain away water, resulting in warmer and drier soils. In contrast, low angle slopes and lower slope positions such as valley bottoms, generally receive less sunlight and collect water, resulting in cooler and wetter soils. Our results are consistent with previous descriptions of species distributions of trees and associated natural vegetation in Interior Alaska (Chapin et al. 2006b). It appears that early stage post-harvest regeneration primarily reflects the long-term natural vegetation distribution, and is likely to reinforce pre-existing landscape patterns following succession. As a result, forest management guidelines and practices should take topography into account as a principal factor. Our results further suggest that attempts at forest type conversion through management practices are likely to have only limited success.

The predicted low occurrence of white spruce in post-harvest regeneration at low elevations and near water may appear somewhat puzzling, at first. In the study area, low-elevation, floodplain sites generally support productive white spruce stands (Magoun and Dean 2000; Viereck et al. 1993). Forest succession along major rivers is generally primary succession initiated by flooding (Chapin et al. 2006a). Primary succession in floodplain forests in Interior Alaska often begins with willow and alder dominance followed by balsam poplar (Viereck et al. 1993). We did not include these species in this analysis. White spruce establishment can occur in the early stage of succession in floodplains but white spruce is intolerant to flooding and silt deposition (Viereck 1970). As a result, the probability of successful establishment of white spruce, a main species in floodplain succession, is low in the frequently flooded zone nearest water (Chapin et al. 2006a). These factors produced a zone of no apparent regeneration near water in our model. By contrast, in upland succession none of our modeled tree species were affected by these factors (Shenoy et al. 2011). Although our sampling included post-harvest regeneration in both floodplains and uplands, the majority of sample units are in uplands (22 or 24 out of 30 units in uplands). Studies based on sampling of additional floodplain harvest units would help resolve this issue.

Management practices in experimental plots have been shown to create differences in post-harvest regeneration in Interior Alaska (Cole et al. 1999; Wurtz and Zasada 2001; Youngblood and Zasada 1991). It appears that the practices examined in this study have relatively low influence on successful prediction of post-harvest regeneration at the landscape scale. Previous studies of post-harvest regeneration in Interior Alaska generally have been experimentally carried out on single site types and so have not considered changes in ecological factors that occur across landscapes (Cole et al. 1999; Wurtz and Zasada 2001; Youngblood and Zasada 1991). In addition, the results of such experimental silvicultural studies vary. This inconsistency is probably due to other, largely environmental, factors that were not explicitly accounted for in such studies, such as topography and spatial components. We believe that forest management practices do influence post-harvest regeneration, but because management influences are weaker than environmental controls we conclude that it is not possible to predict regeneration outcomes in operational practice in Interior Alaska by the type of management practices alone.

Soil subgroup affected predictions of post-harvest regeneration, especially for aspen (Figure 4.3a-c), possibly because it was a categorical rather than scalar predictor. Harvest units sampled in this study were mostly on well-drained permafrost free soils (Cryofluvents, Haplocryepts, and Dystrocryepts; over 99% of plots). Soils associated with floodplains supported lower prediction of post-harvest regeneration presence. White spruce and aspen showed strong preference to soils associated with higher elevation (Haplocryepts and Dystrocryepts).

Distance to seed source (forest types) is another important factor affecting post-harvest regeneration success, especially in white spruce (Figure 4.3) because of its limited reproduction ecology and seed dispersal ability (Nienstaedt and Zasada 1990; Youngblood 2012; Youngblood and Max 1992; Youngblood and Zasada 1991). White spruce only regenerates from seeds, and most seeds are dispersed within relatively short distances compared to birch and aspen (Nienstaedt and Zasada 1990). In addition, birch and aspen regenerate asexually from stumps and belowground rhizomes, respectively, and do not rely solely on seedfall (Perala 1990; Safford et al. 1990). Our model showed that white spruce post-harvest regeneration tends to occur more in plots closer to white spruce forest, although the contribution was relatively weak (Figure 4.4f). The model also finds that white spruce occurrence is affected more by distance to birch forest, and the spruce occurrence is lower closer to birch forest (Figure 4.3a and 4.4e). This is perhaps due to high competition near the edge of harvest, especially when the harvest was adjacent to birch forest because of vigorous birch regeneration. Finally, aspen occurrence was greater when closer to aspen forest (Figure 4.3c and 4.4g). Aspen regenerates both from seed and belowground rhizomes, which decreases the dependence on seedfall. The number of stems (ramets) from rhizomes increases when parent stem density is higher (Perala 1990). When adjacent forest contained a mature aspen component, the harvested stand was more likely to retain mature aspen stems to provide seed and asexual stems. It appears that distance to a mature aspen component is a good proxy to predict aspen regeneration.

Post-harvest regeneration is also considerably affected by proximity to artificial landscape factors, including urban area, development, and roads, suggesting that human activities influenced post-harvest regeneration. The great contribution of distance from forest road to successful prediction of birch and aspen occurrence, which is particularly high within 50 m of a forest road, appears to be due to substantial exposure of mineral soils along roadsides. In fact, dense birch regeneration along forest roads was particularly noticeable during sampling. The influence of distance to artificial features on species occurrence also might be a result of the selection of areas for harvest. In Interior Alaska the forest road system is limited. As a result, harvest units tend to be selected in areas near existing roads (Morimoto 2016), which are closer to developed areas.

Temperature and precipitation of specific months are strong contributors to post-harvest regeneration predictions for each species (Figure 4.3a-c). In particular, May precipitation is the most important predictor for high occurrence of aspen (Figure 4.3c). The predicted occurrence in regeneration for all three tree species - white spruce, birch, and aspen - increased where precipitation in May is lower and where precipitation in late summer is higher (Figure 4.4m-o). In general, predicted regeneration of white spruce, birch, and aspen is greater when temperature in August is cooler (Figure 4.4p). This is consistent with the repeatedly demonstrated growth limitation of mature boreal trees by temperature-induced drought stress in the study area (Barber et al. 2000; Juday et al. 2015; Juday and Alix 2012; McGuire et al. 2010). However, the relationships between post-harvest regeneration and climate need to be interpreted with caution because resolution of the climate data grid was much larger (771-m) than the sampling grid (50-

m) and topographic variables (5-m). In addition, climate data is downscaled using a limited amount of weather station data (SNAP 2015). Given this situation, the information content of vegetation distribution patterns may actually be a useful input in improving the spatial resolution of downscaled climate data.

Year of harvest was the most important predictor for presence/absence of white spruce natural regeneration (Figure 4.3a). Relative occurrence of white spruce natural regeneration increased dramatically 14-15 years following harvest, suggesting white spruce recruitment continues for a relatively long time following harvest. White spruce recruitment is highly dependent on the sporadic seed crop and its viability, and the combination of large seed crops and high seed viability generally occurs only every 10-12 years in Interior Alaska (Roland et al. 2014). White spruce natural regeneration is limited when disturbance occurs in no or low white spruce seed crop years (Viereck and Schandelmeier 1980). Currently, the success of natural regeneration following harvest is decided based on the AKDOF regeneration survey within seven years post-harvest. However, based on our finding, seven years might be too early to evaluate the success of white spruce natural regeneration. Evaluation of post-harvest regeneration appears to be most effective when it is conducted between 10-15 years following harvest because of the continued natural recruitment.

4.5.3. Scenarios of Forty Years of Post-Harvest Regeneration

Developing prediction-based scenarios of post-harvest natural tree regeneration is a useful way to identify areas that require greater care in the implementation of management practices under a changing climate (Ferguson and Carlson 1993; Miina and Saksa 2013). The effects of climate warming on tree growth are rather complex and even variable (Barber et al.

2000; Juday et al. 2015; Lloyd et al. 2013; Wilmking et al. 2004). As a result, more sophisticated research on the relationship between climate parameters and early tree growth is necessary (Grossnickle 2000). Nevertheless, this is the first study in Interior Alaska examining the effects of climate change on early post-harvest regeneration, which provides a basis for future research.

Based on the scenarios we analyzed, strong climate warming reduces the occurrence of natural tree regeneration following harvest. The reduction is moderate for white spruce and aspen, and severe for birch, compared to historical conditions (Figure 4.5a-c). Areas that would experience white spruce regeneration failure under strong climate warming are low and moderate elevation locations along the major rivers, valleys, and the south half of major ridges. These locations are characterized by the warmest July temperatures (Figure 4.6a) and low to moderate July precipitation (Figure 4.6b). Post-harvest birch regeneration failure is widespread across low elevation valleys and ridges with high July temperatures (Figure 4.6c) and low precipitation (Figure 4.6d) with the exception of the northwest portion of the study area. These results are consistent with the projections of changes in natural vegetation under climate warming in a number of studies (e.g. Lloyd et al. 2013).

By contrast, post-harvest regeneration appears to be more successful under the more moderate climate warming scenarios, B1 and A1B, compared to historical climate (Figure 4.5a-c). Because of the extremely cold climate in Interior Alaska, apparently moderate warming improves the growth of populations of trees that occur in areas with temperatures below the optimum for the species (Juday et al. 2015). State forest lands of the study area cover a broad landscape region with a range in elevation and resulting temperature and precipitation factors. Even though currently combinations of temperature and precipitation in parts of this region are marginal for the growth of boreal tree species in studies that highlight the vulnerability of boreal trees to drought and warming (Barber et al. 2000; McGuire et al. 2010), many parts of the state forest lands are cooler and experience higher precipitation. As a result, trees occurring in these currently more favorable climatic environments of the state forest presumably are less vulnerable to warming. However, once climate change reaches a threshold (Costantini et al. 2014), temperatures across the wider range of landscapes would be beyond the optimal climate for tree regeneration, especially for birch and aspen, and would enter the range of negative growth response (Figures 4.5 and 4.6 a-d; Juday et al. 2015). At the smaller landscape scale, increased temperature results in greatest regeneration failure in areas with least favorable environments and landscape positions (Figure 4.6a-d). As a result, identifying the location and landscape positions of current environments that are least favorable for successful tree regeneration highlights areas that are the most vulnerable to further temperature increases.

Management practices produce some differences in post-harvest regeneration, even though the influence on post-harvest regeneration was smaller compared to environmental factors (Figure 4.5a-c). Clearcutting and site preparation increase the probability of post-harvest regeneration, especially for white spruce and birch (Figure 4.5a-b). In particular, the positive effect of site preparation on probability of white spruce regeneration is sufficient to overcome the greater negative effect of A2 and A1B scenario level of warming compared to A1B and B1, respectively (Figure 4.5a). Even so, planting white spruce seedlings may become more important to supplement tree regeneration, especially in plots or areas that were predicted to have low probability of tree regeneration with clearcutting and/or site preparation.

In the study area, following the harvest of mature white spruce, white spruce is the most successful species (highest relative occurrence of recruitment within 40 yrs) in post-harvest regeneration. The species with the lowest predicted recruitment in harvested white spruce stands is aspen, under any climate and management scenario over the next several decades (Figure 4.5c). It is important to note, however, that the scenarios only considered post-harvest regeneration in previously white spruce dominated stands. As a result, future aspen recruitment might be successful in other portions of landscape, particularly where non-spruce types currently dominate. In addition, the predicted lower white spruce regeneration failure under increased temperature may be partly due to the high dependence of white spruce predictions on year of harvest (Figure 4.3a). In this study, we built scenarios of regeneration 38 years after harvest, which allows the accumulation of white spruce over a prolonged recruitment period. This time period also reduces hardwoods through early stages of competition, maximizing the relative abundance of white spruce regeneration. Significantly, the level of climate warming produced under the A2 climate scenario is likely to strongly affect hardwood regeneration. Recent studies of climate sensitivity have focused on white spruce (Barber et al. 2000; Juday et al. 2015; McGuire et al. 2010; Wilmking et al. 2004), but it appears that native boreal hardwoods also would be affected very negatively by plausible temperatures increases of the next half-century (Figure 4.5b-c). Early successional hardwood forest is an important component in the landscape for sustaining biodiversity. Our results clearly suggest that further study of the effects of climate warming on hardwood species, particularly productive stands accessible for timber management, is necessary.

It is somewhat surprising that post-harvest tree regeneration in the central Interior Alaska boreal region appears to be successful under the current climate and management regime, particularly in light of the reduced growth of mature white spruce under recent temperature increases (Barber et al. 2000) and the low regeneration management inputs in the region (Morimoto 2016). However, this study demonstrates that failure of tree regeneration is likely to occur across the landscape with only modest additional warming, particularly for birch. Plausible scenarios of temperature increases by the year 2100, which is well within the rotation period of tree crops that were regenerated by forest management that are the subject of this study, include levels of warming up to 10 C in central Interior Alaska (IPCC 2014; Kaplan et al. 2003). Such warming would be beyond the apparent range of tolerance of the major boreal tree species (Thompson et al. 1999) where forests are well developed today, but within the suitable range in far western Alaska near the Bering Sea (Juday et al. 2015). Tree regeneration that is apparently successful today also faces elevated future risks from insect-caused tree mortality (Dale et al. 2001; Weed et al. 2013), and wildland fire (Bachelet et al. 2005; Joly et al. 2012). Finally, the market demand in Alaska for boreal wood products is uncertain, and has changed significantly in the 40 years that professional forestry has occurred (Wurtz et al. 2006). As a result, it would be prudent for forest management to be prepared for a biome shift that appears likely to occur in the near future (Murphy et al. 2012).

4.6. Acknowledgements

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4.7. Tables

Table 4.1 State's stocking standard for Interior Alaska.

DBH (cm)	Minimum Stocking Standard (trees ha^{-1})
Seedlings	1,112
2.5-15.2	495
15.2-22.9	420
>22.9	297

Table 4.2 List of sample units.

Unit	Size (ha)	# plots calculated	# plots sampled	Logged year	Harvest type	Site Preparation	Reforestation
NC-120	10.4	41	41	1975	Partial cut	None	Plant
NC-93	17.9	76	35	1975	Partial cut	None	Natural
NC-190	5.1	22	22	1977	Clearcut	Scarify	Natural
NC-126	5.7	22	22	1978	Partial cut	None	Natural
NC-140-17	2.5	8	8	1979	Clearcut	None	Natural
NC-249	5.0	22	22	1980	Clearcut	Scarify	Natural
NC-362	4.4	15	15	1981	Partial cut	None	Natural
NC-140-38	1.5	7	7	1982	Clearcut	Scarify	Natural
NC-395	5.1	21	21	1983	Clearcut	None	Natural
NC-490	8.4	32	32	1985	Clearcut	None	Natural
NC-556	6.6	26	26	1986	Clearcut	None	Plant
NC-305	3.5	11	11	1987	Partial cut	Scarify	Plant
NC-705	11.0	44	44	1989	Clearcut	Scarify	Plant
NC-454	20.4	87	44	1991	Clearcut	Scarify	Plant
NC-740	1.9	8	8	1991	Clearcut	None	Plant
NC-709	17.2	71	35	1991	Clearcut	Scarify	Plant
NC-842	2.1	7	7	1992	Partial cut	None	Natural
NC-733	30.3	120	44	1992	Clearcut	Scarify	Plant
NC-702	2.0	9	9	1993	Clearcut	None	Plant
NC-747	8.0	31	31	1994	Clearcut	None	Plant
NC-750	9.8	41	41	1995	Clearcut	Scarify	Plant
NC-1085	22.6	94	47	1996	Partial cut	Scarify	Plant
NC-1137	13.5	55	29	1997	Clearcut	None	Plant
NC-927	22.5	90	43	1998	Partial cut	None	Plant
NC-760	3.4	13	13	1998	Partial cut	None	Natural
NC-1129	6.0	22	22	1999	Partial cut	None	Plant
NC-1090	1.4	7	7	1999	Partial cut	None	Natural
NC-1135	11.7	49	49	2002	Partial cut	None	Plant
NC-1116	2.4	9	9	2003	Partial cut	Scarify	Natural
NC-1143	6.7	28	28	2004	Partial cut	None	Natural

Table 4.3 List of response and predictor variables.

Variable	Description	Unit	Data source
Response variables			
Presence/absence	Presence/absence of white spruce, birch, and aspen	Category	Field sampling
Predictor variables			
Harvest type	Harvest type: clearcut/partial cut	Category	AKDOFFMD
Site preparation	Ground treatment type: none/mechanical site preparation	Category	AKDOFFMD
Reforestation	Reforestation type: natural/planting white spruce seedlings	Category	AKDOFFMD
Year	Year since harvest: 10-39	Continuous	AKDOFFMD
Size	Size of harvest unit	hectare	AKDOFFMD
Edge	Distance to edge of harvest unit	km	AKDOFFMD
White spruce	Distance to white spruce forest	km	AKDOF vegetation map
Birch	Distance to birch forest	km	AKDOF vegetation map
Aspen	Distance to aspen forest	km	AKDOF vegetation map
Water	Distance to water	km	AKDOF vegetation map
Highway	Distance to highway	km	AKDOF vegetation map
Forest road	Distance to forest road	km	AKDOF vegetation map
Urban	Distance to urban area	km	AKDOF vegetation map
Development	Distance to development (power line, mine etc.)	km	AKDOF vegetation map
Elevation	Elevation	m	GINA DEM
Slope	Slope	degree	GINA DEM
Aspect	Aspect	Category	GINA DEM
TPI	Topographic Position Index	Continuous	GINA DEM
Soils	Soil subgroup	Category	NRCS
May temp	Average temperature of May	ºC	SNAP
June temp	Average temperature of June	ºC	SNAP
July temp	Average temperature of July	ºC	SNAP
Aug temp	Average temperature of August	ºC	SNAP
May precip	Precipitation sum of May	mm	SNAP
June precip	Precipitation sum of June	mm	SNAP
July precip	Precipitation sum of July	mm	SNAP
Aug precip	Precipitation sum of August	mm	SNAP

Table 4.4 The performance of predictive models of white spruce, birch, and aspen presence/absence, including contingency table, true negative and true positive rates, average accuracy, and area under curve of ROC.

		Prediction				
		Absent	Present	%Correct	Accuracy	AUC
White spruce	Absent	239	93	71.99 %	0.72	0.79
	Present	108	286	72.59 %		
Birch	Absent	176	91	65.92 %	0.68	0.74
	Present	138	321	69.93 %		
Aspen	Absent	491	92	84.22 %	0.84	0.92
	Present	22	121	84.62 %		

4.8. Figures

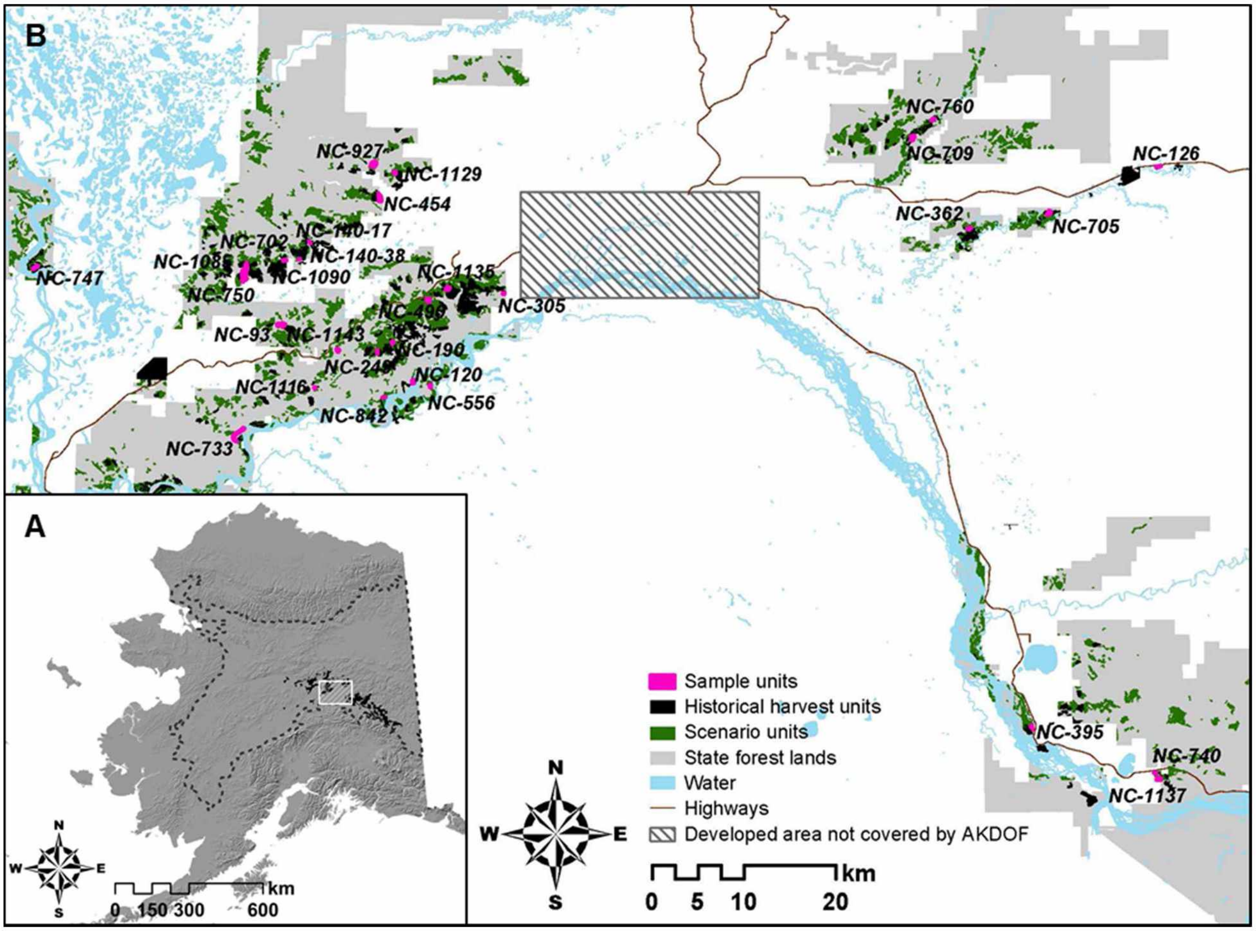

Figure 4.1. Maps of study area. (a) Study area (shaded box) located in the Tanana Valley State Forest and forest classified land (black polygons) within Interior Alaska (dashed boundary). (b) Distribution of sample units, scenario units, and historical harvest units on state forest lands. NC- followed by numbers represent sample units.

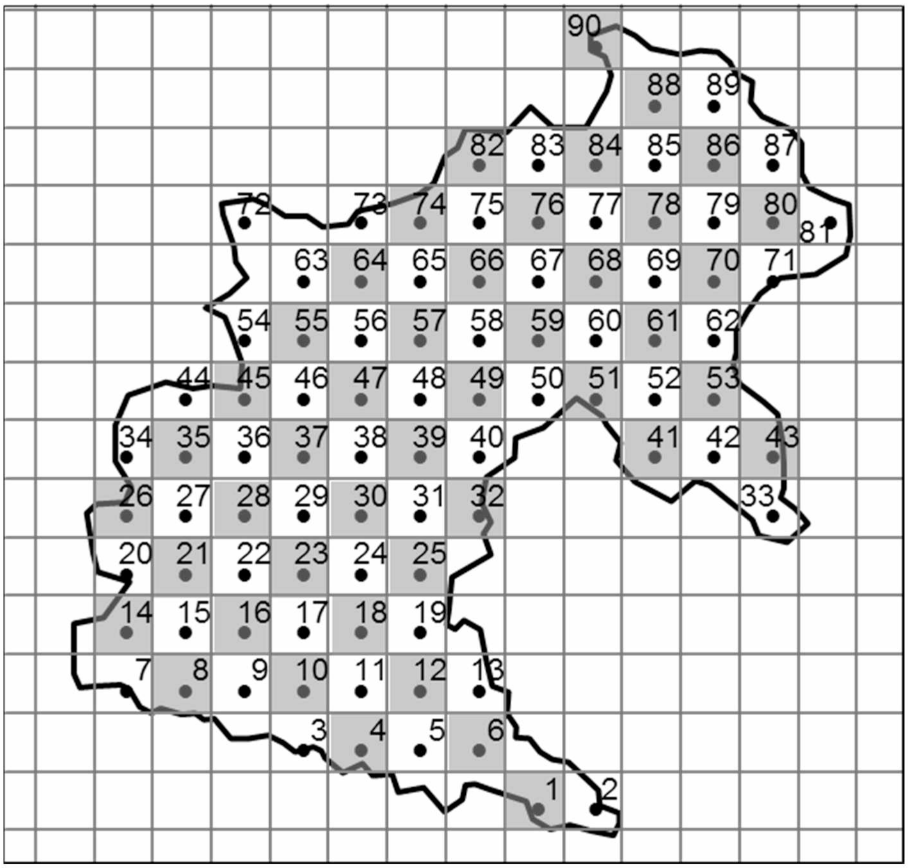

Figure 4.2. Sampling design. The size of the grid is 50 m. Dots represent plots and the numbers above them represent plots numbers. In units with more than 50 plots, every other plot was selected as below (shaded cells).

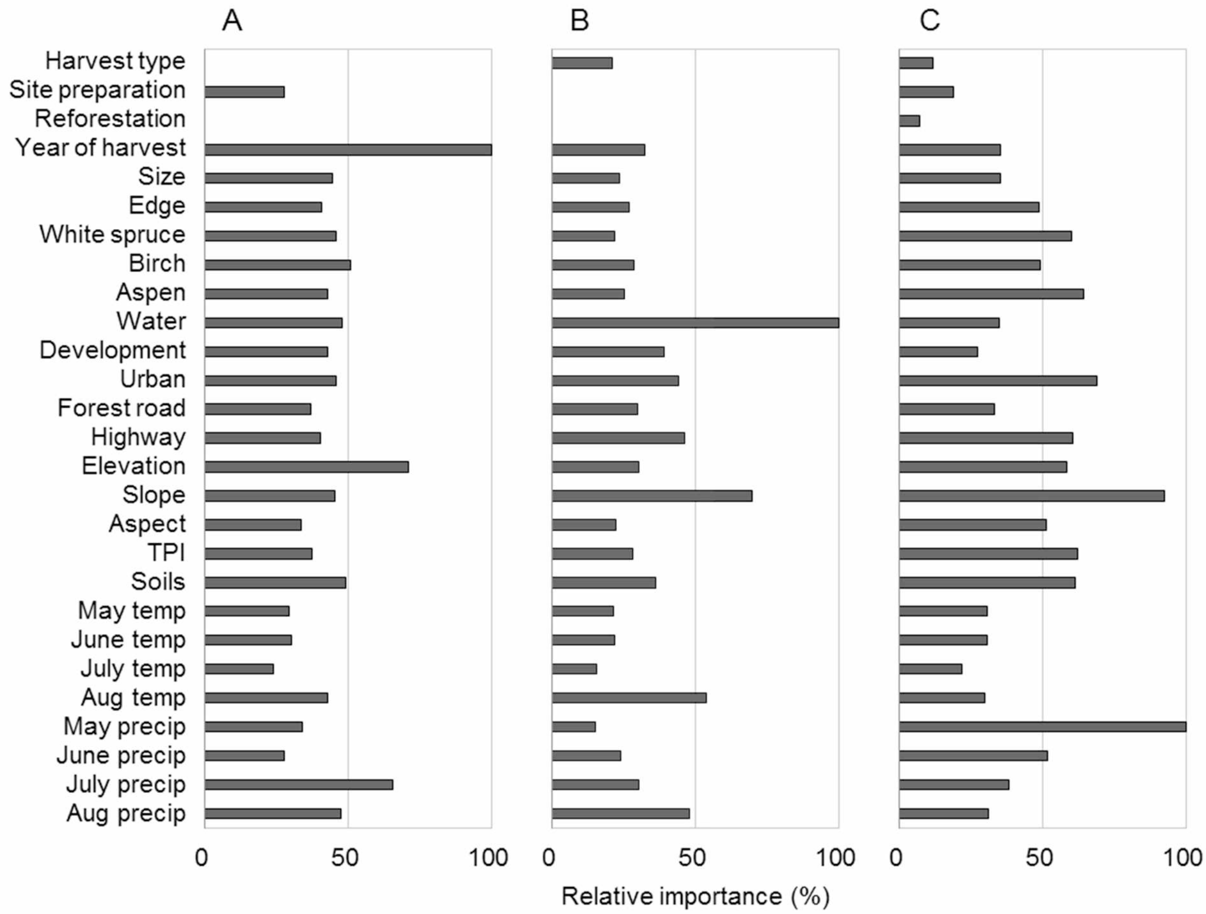

Figure 4.3. Relative variable importance of predictors for predictive models of (a) white spruce, (b) birch, and (c) aspen. The importance value for any predictor is determined by averaging the number of times it is selected as a tree node over all trees and the squared improvements in error rate resulting from these nodes (Hastie et al. 2009). A relative importance value of 100 is assigned to the most important predictor, and relatively scaled values are assigned to other predictors based on the most important predictor.

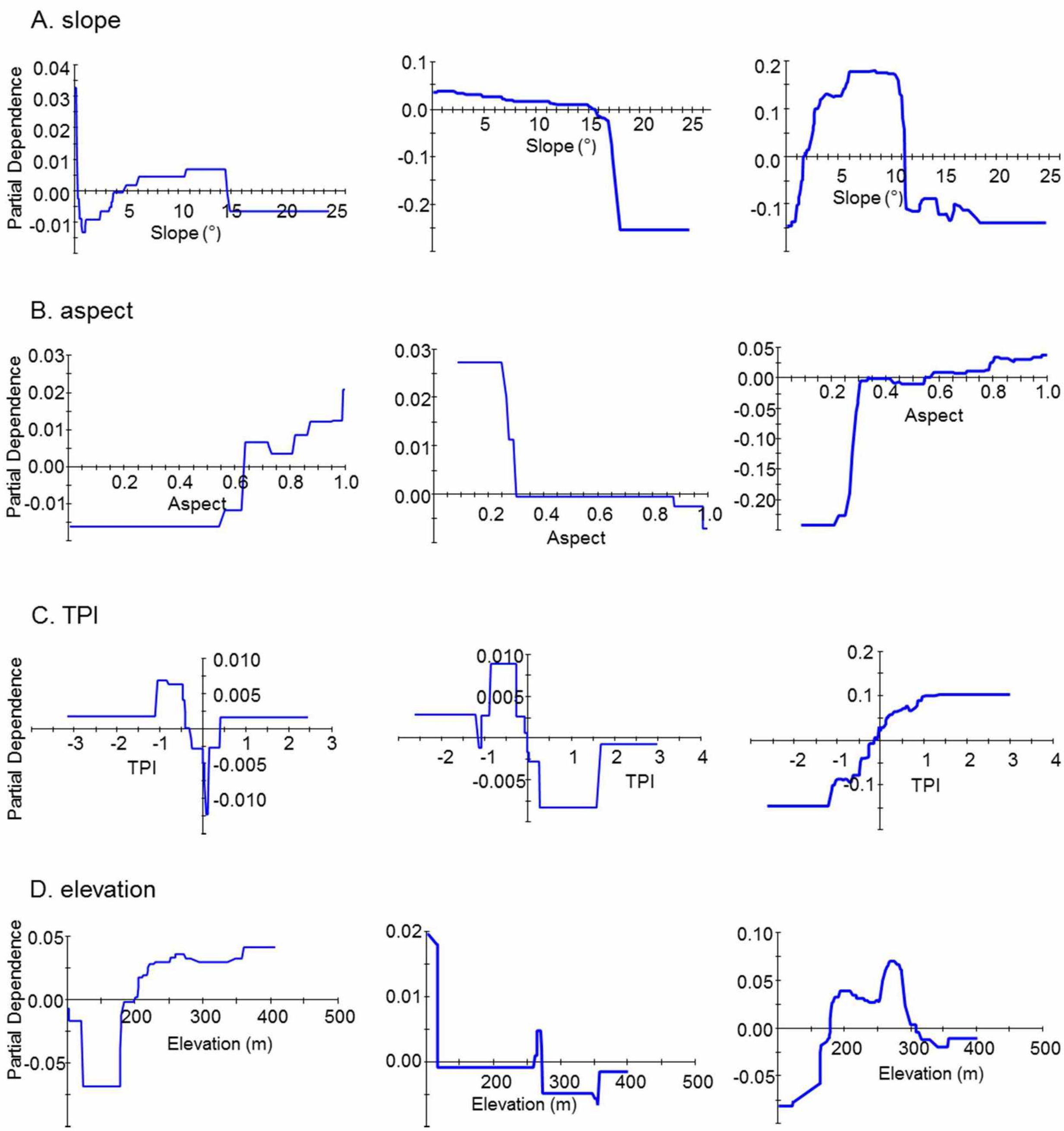

Figure 4.4. Partial dependence plots of selected predictors for white spruce (left), birch (middle), and aspen (right column). Partial dependence plots show the relationship between the response and any given predictor by representing the dependence of the response on the predictor variable when all other variables are held at their mean (Hastie et al. 2009). Y-axes are partial dependence value of prediction being an index between presence/high and absence/low.

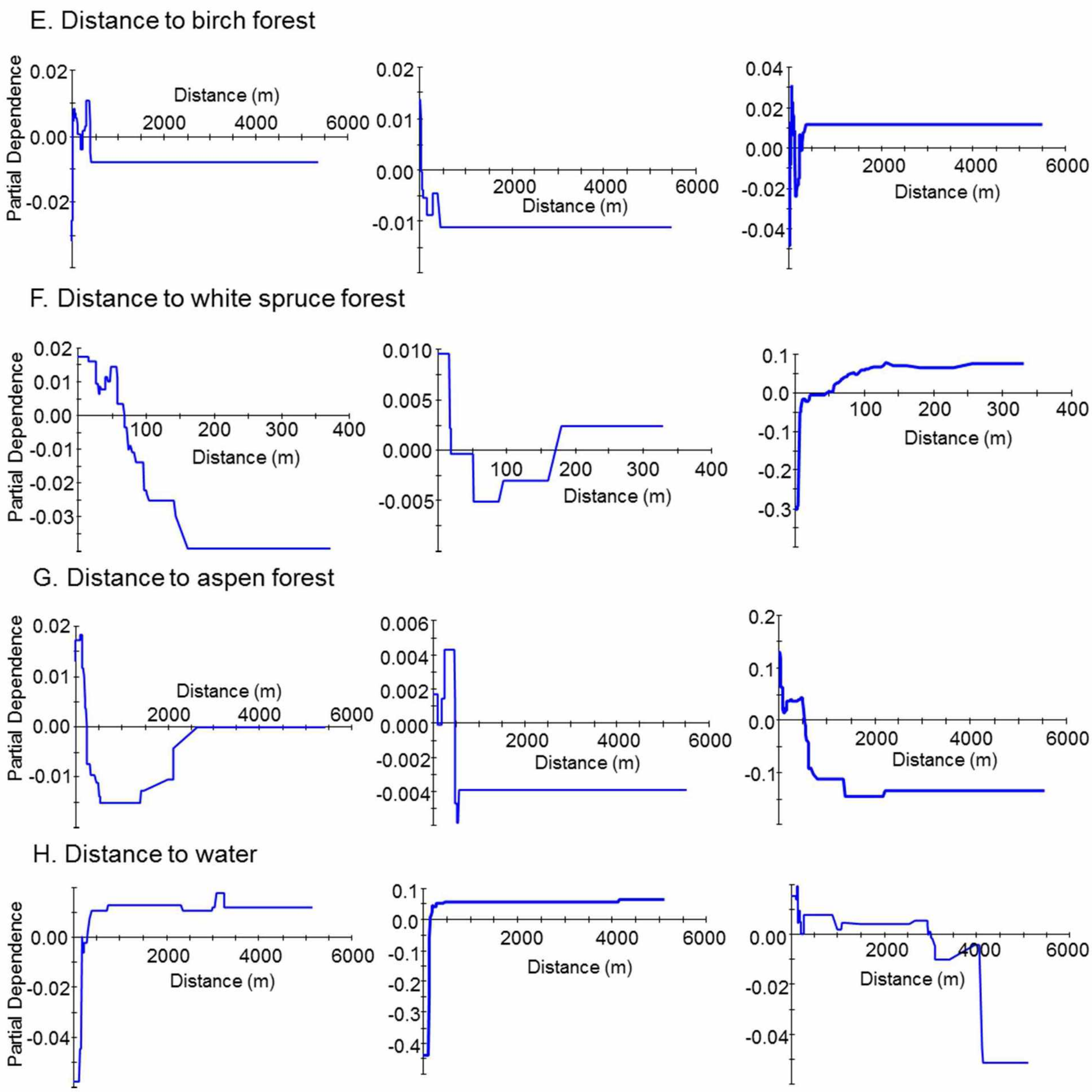

Figure 4.4 cont.

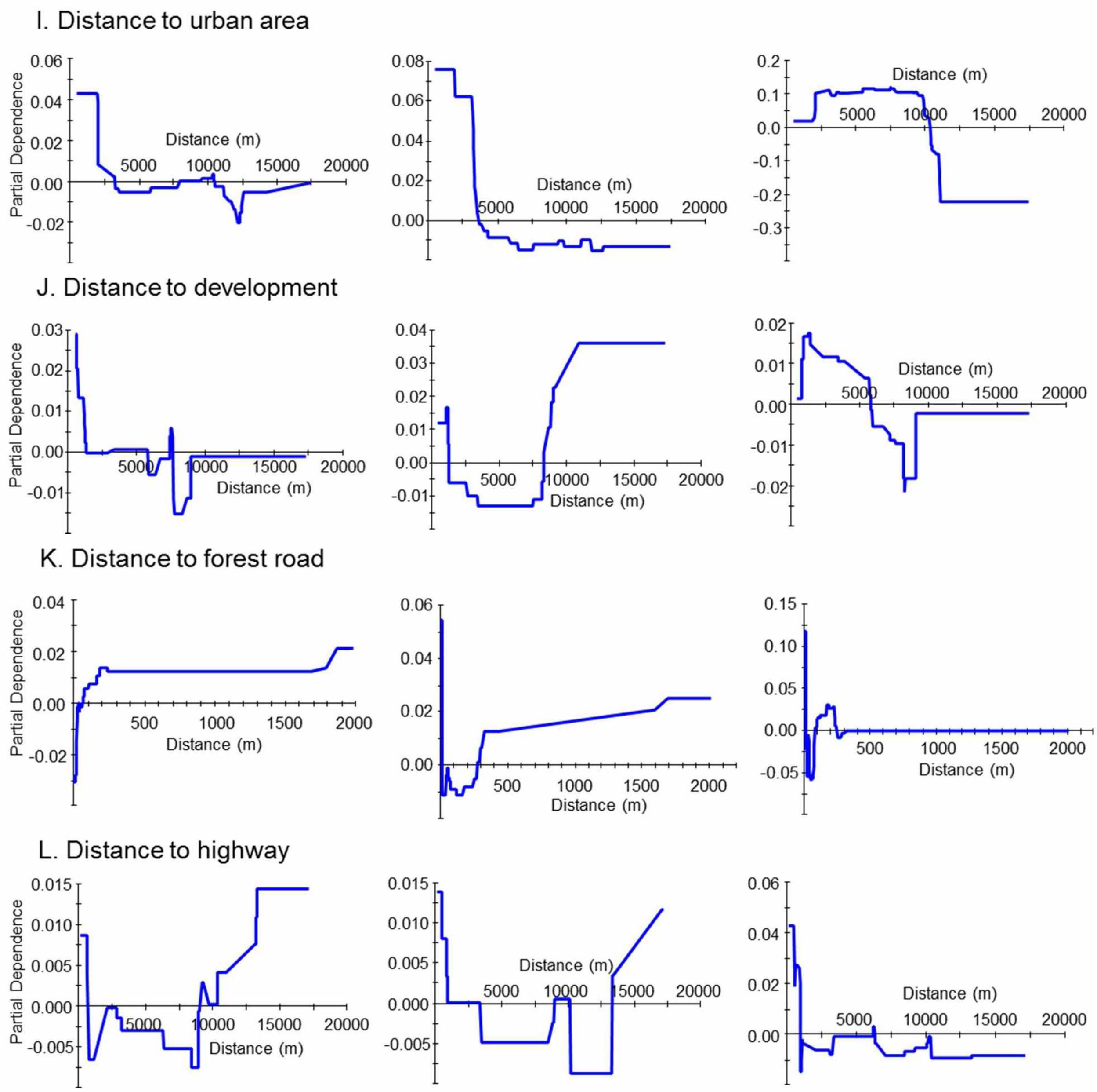

Figure 4.4 cont.

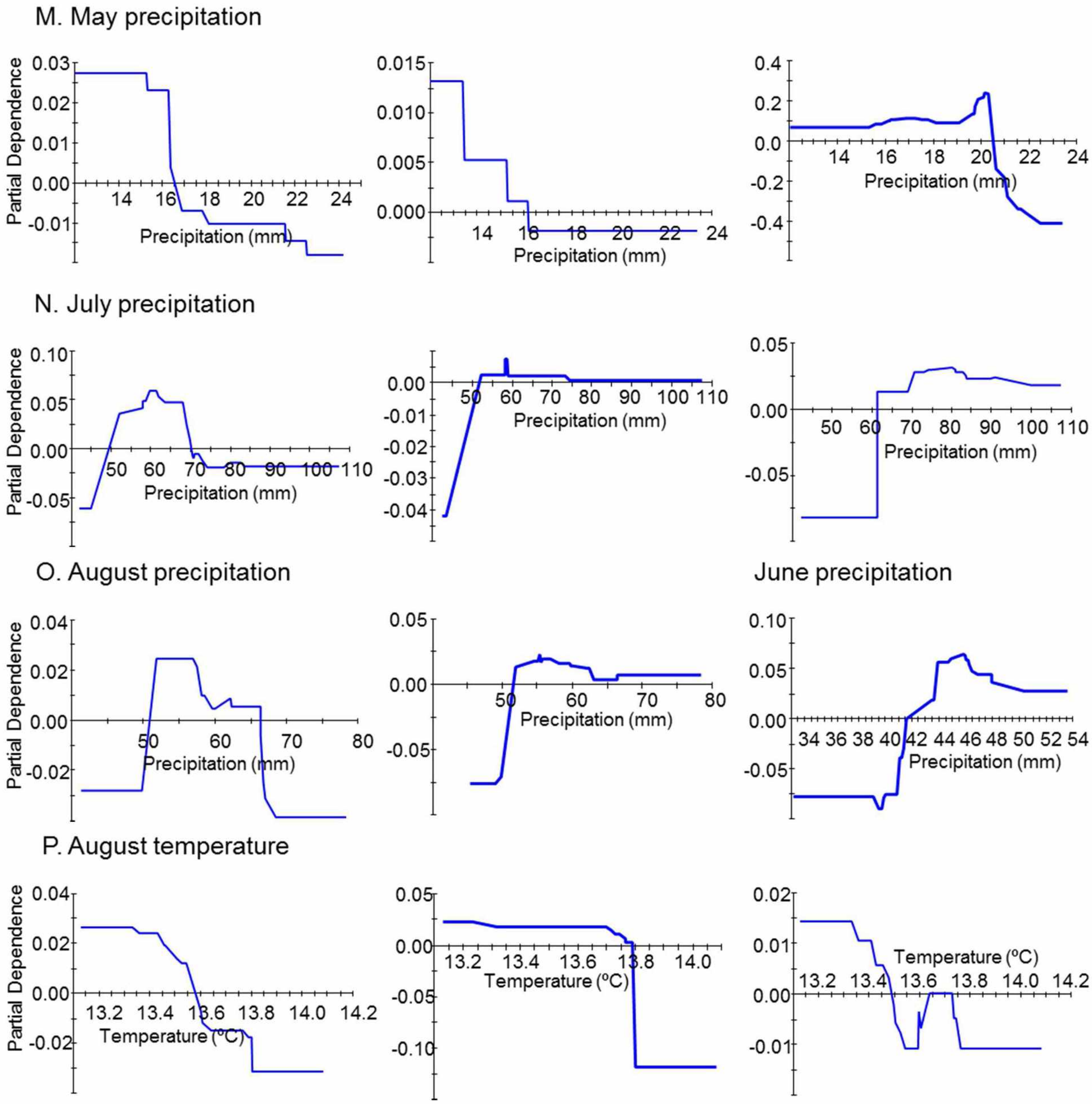

Figure 4.4 cont.

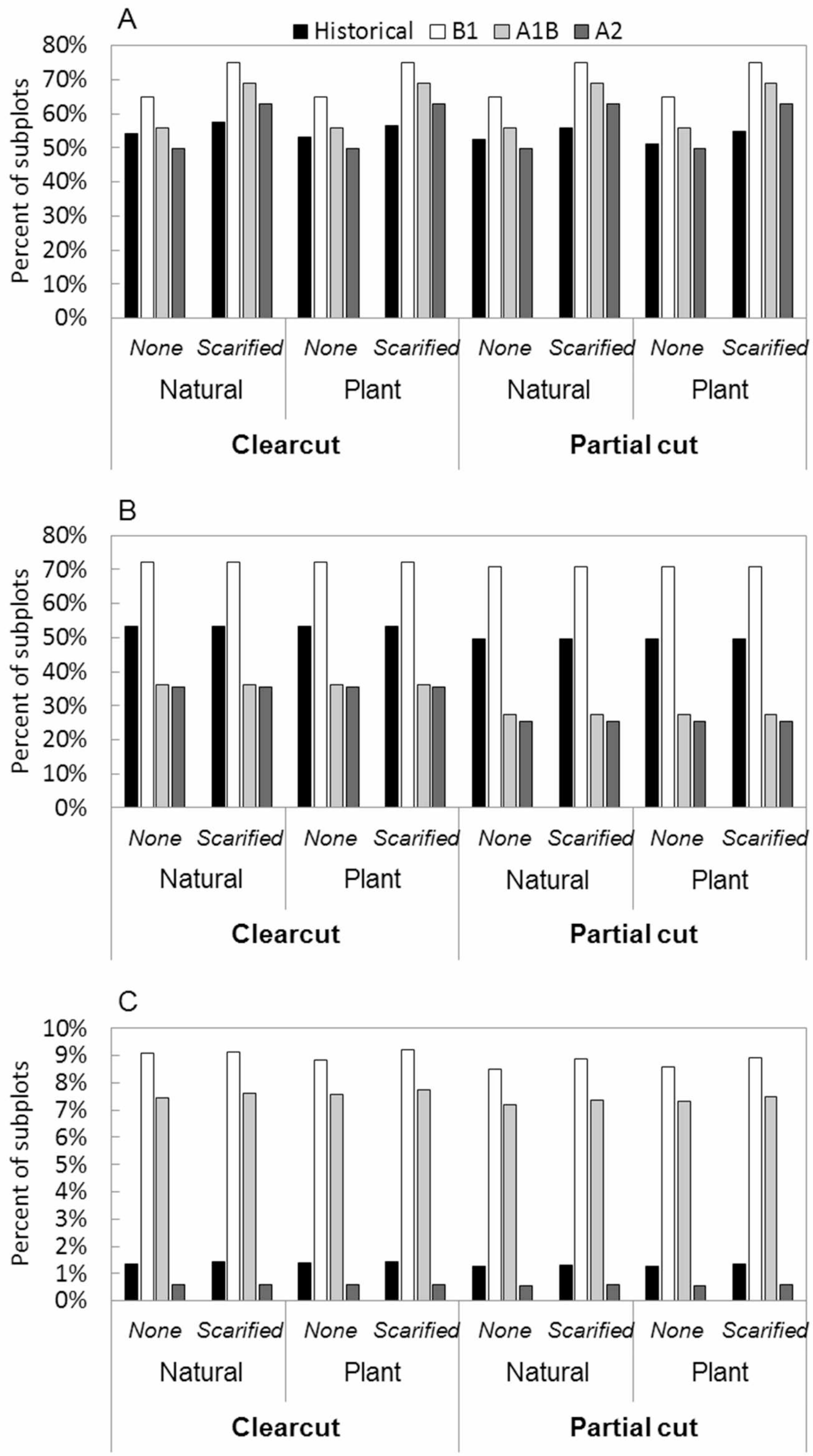

Figure 4.5. Percent of scenario plots that were predicted to contain post-harvest natural regeneration of (a) white spruce, (b) birch, and (c) aspen under projected historical climate and the future climate scenarios (B1, A1B, and A2).

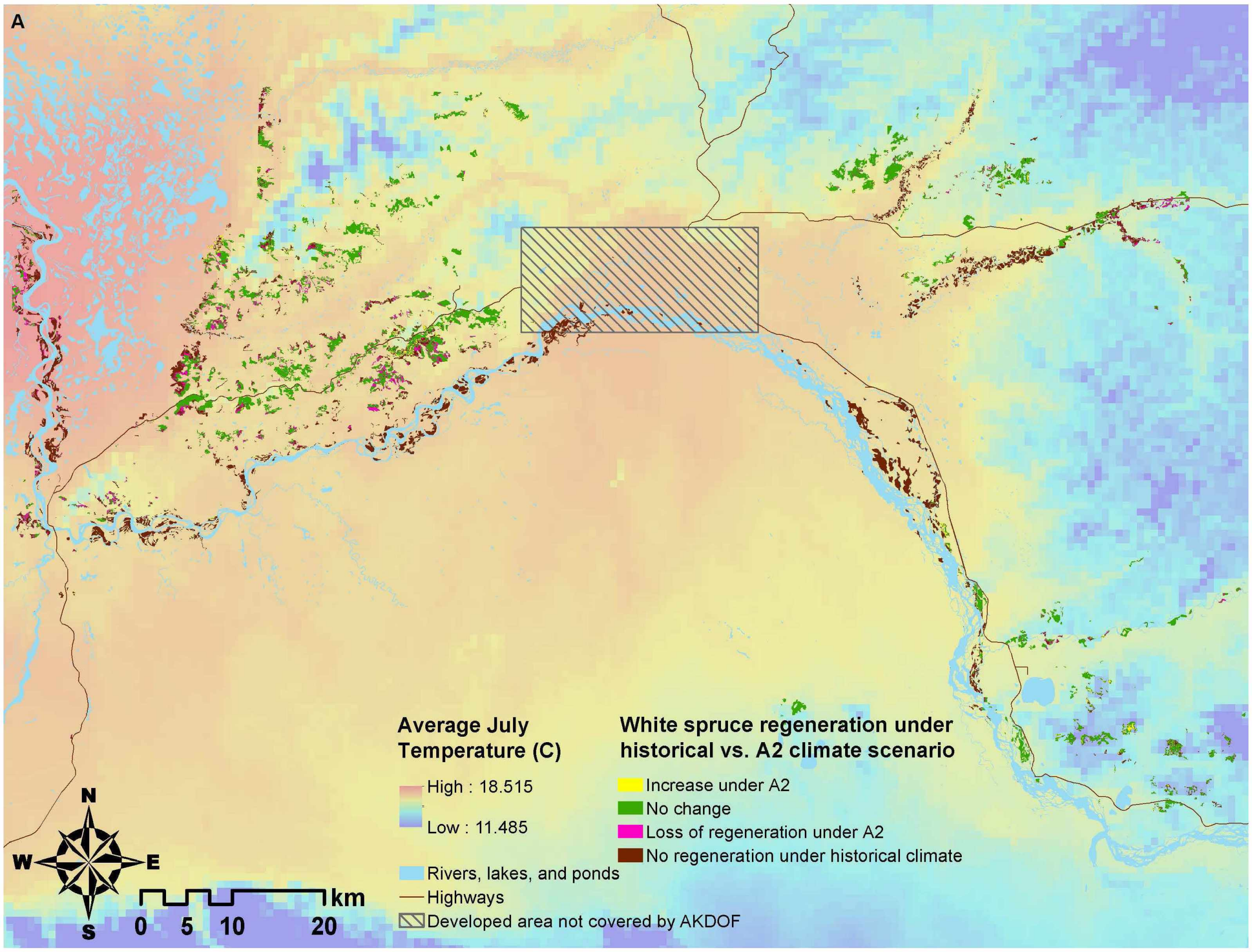

Figure 4.6. Maps showing the differences in presence/absence predictions of (a) white spruce with historical average July temperature, (b) white spruce with historical average July precipitation, (c) birch with historical average July temperature, and (d) birch with historical average July precipitation between historical climate and A2 scenario climate. All the scenarios are assumed to have received clearcutting, no site preparation, and natural regeneration.

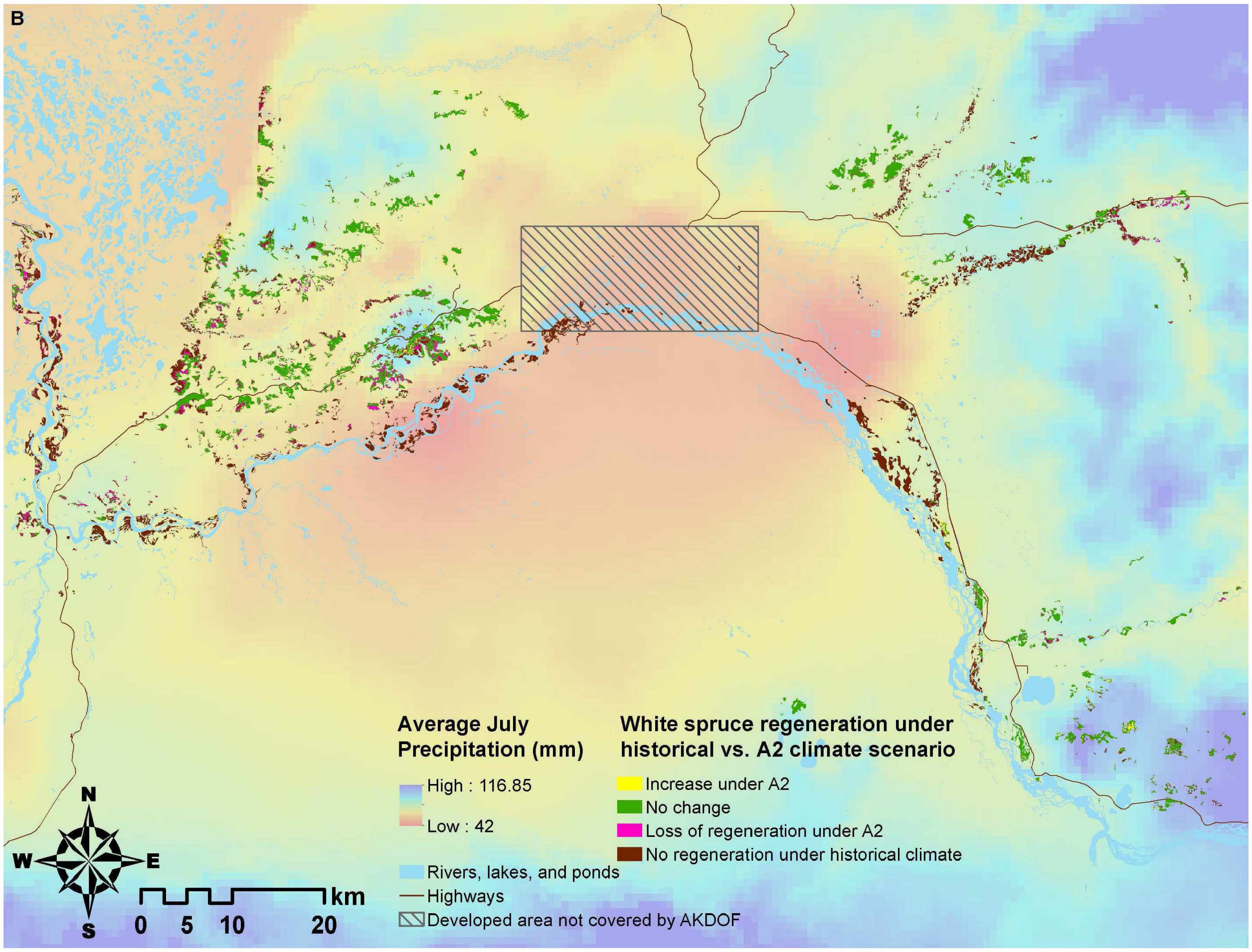

Figure 4.6 cont.

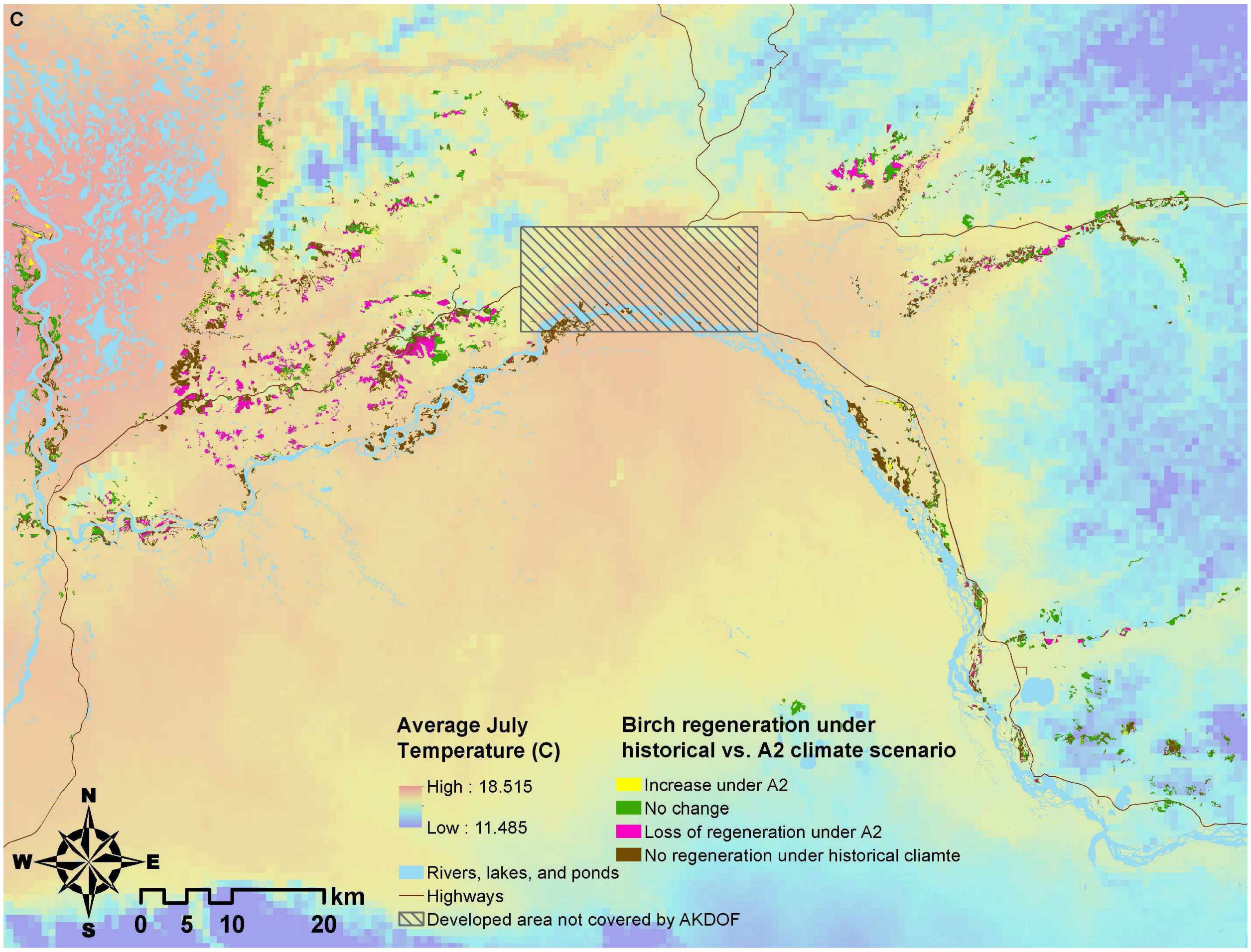

Figure 4.6 cont.

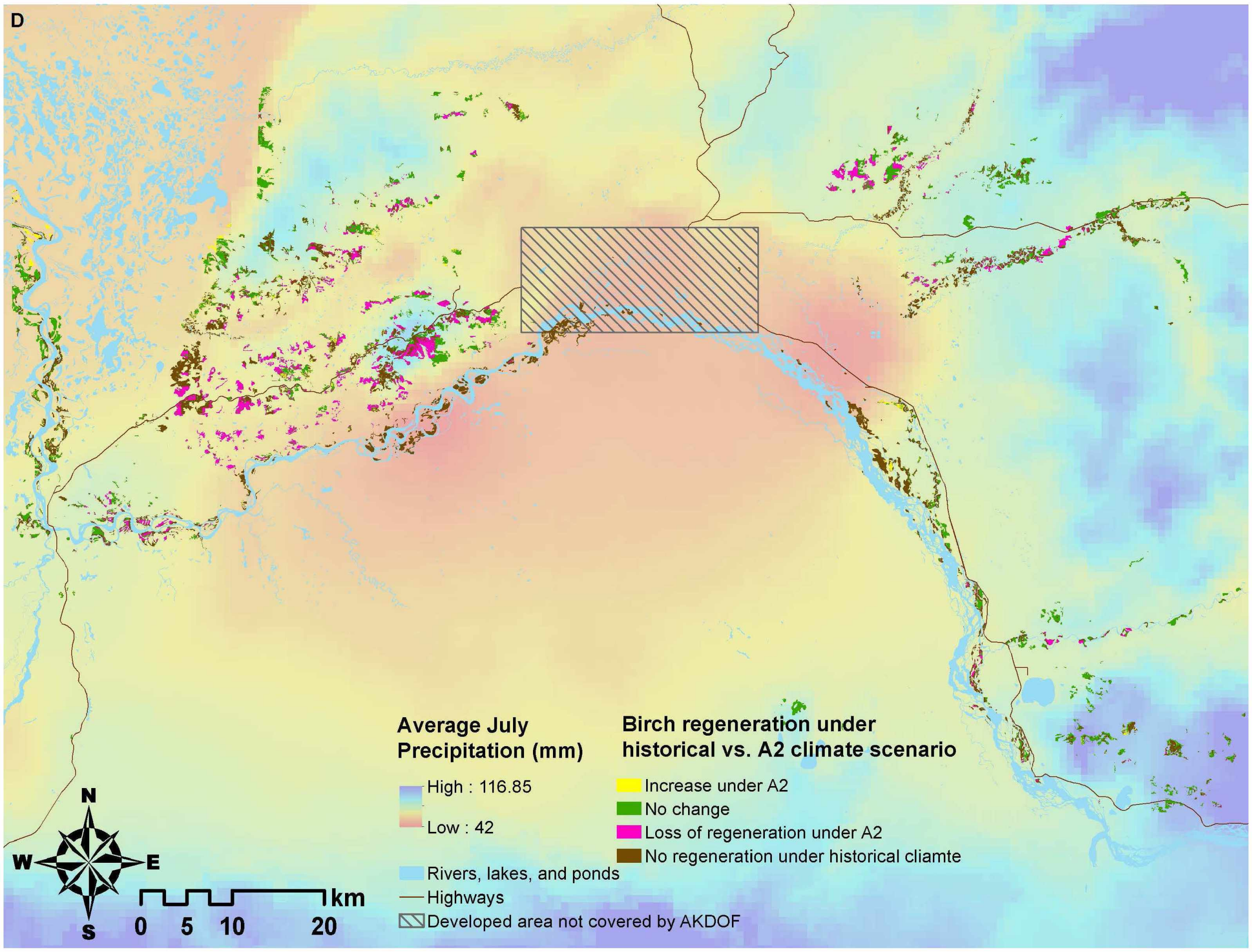

Figure 4.6 cont.

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4.10. Appendix

Appendix 4.1. List of 24 scenarios. Each scenarios was applied to each species.

Scenario	Climate	Harvest type	Site preparation method	Reforestation technique
B1 CSP	B1	Clearcut	Scarified	Planted
B1 CSN				Natural
B1 CNP			Not scarified	Planted
B1 CNN				Natural
B1 PSP		Partial cut	Scarified	Planted
B1 PSN				Natural
B1 PNP			Not scarified	Planted
B1 PNN				Natural
A1B CSP	A1B	Clearcut	Scarified	Planted
A1B CSN				Natural
A1B CNP			Not scarified	Planted
A1B CNN				Natural
A1B PSP		Partial cut	Scarified	Planted
A1B PSN				Natural
A1B PNP			Not scarified	Planted
A1B PNN				Natural
A2 CSP	A2	Clearcut	Scarified	Planted
A2 CSN				Natural
A2 CNP			Not scarified	Planted
A2 CNN				Natural
A2 PSP		Partial cut	Scarified	Planted
A2 PSN				Natural
A2 PNP			Not scarified	Planted
A2 PNN				Natural

Chapter 5. Adaptive Approach to Forest Harvest Management in Boreal Alaska under Rapid Climate Change[1]

5.1. Abstract

Alaska's boreal forest is fairly intact ecologically and provides various services but is also experiencing rapid climate change. This study offers adaptive management approaches using the experience of 40 years of forest harvest and regeneration management as a basis to prepare for the future climate by synthesizing accumulated knowledge, and applying it to the needs and challenges of today. Forest harvest disturbances were concentrated near roads, and much smaller in area than wildfire both individually and in overall total. Forest harvesting also reduced structural and species diversity within stands, when compared to wildfire. Post-harvest regeneration followed a similar successional pattern to that seen following fire, and has been largely successful, especially following clearcutting and site preparation. However, climate warming is likely to cause regeneration failure across landscapes within the planned rotation. As a result, monitoring growth of regeneration, identifying optimal climatic sites and resilient genes and species, and allowing biome shift in some parts of landscape is now necessary.

5.2. Management and Policy Implications

Understanding the natural processes in Alaska's boreal forest provides a basis for adaptive management of landscapes in which forest harvest occurs. Forest harvest management in boreal Alaska is low-input and concentrated near road systems, where fire suppression is most

[1] Miho Morimoto and Glenn P. Juday, Implementing adaptive forest harvest management in boreal Alaska under rapid global change. Prepared for submission in Journal of Forestry.

active. In this managed area, harvesting can improve forest health, recoup economic values, and reduce fire risks as forests continue to age. Forest harvest removes or depletes habitat for some plant and wildlife species and creates habitat for others. Properly designed harvest activity, including habitat retention, can minimize loss of essential ecological services, such as landscape and structural diversity. Post-harvest regeneration has been largely successful based on the state regeneration stocking standard, particularly following clearcutting and site preparation, despite a limited amount of planting. Forest harvest management needs to be adjusted according to overall goals and to timing of white spruce seed crops, then monitored and adjusted as managed area expands. Adaptive management in boreal Alaska is particularly necessary because regeneration failure is likely soon due to warming. We offer some potential adaptation approaches: (1) identifying new sites and regions that will experience sustained or enhanced growth potential – e.g. higher elevations, less exposed aspects, locations further west, (2) monitoring growth and health of existing post-harvest regeneration, (3) initiating genetic studies to find the most adaptable tree populations, (4) accepting biome conversion of forest to shrubland or grassland and finding their product opportunities, and (5) exploring potential of native species not previously present in Alaska.

5.3. Introduction

Boreal forests provide various ecological services, including climate regulation, biodiversity, and nutrient cycling (Bonan *et al.*, 1992), and essential social and economic values for human lives, particularly for indigenous people (Chapin *et al.*, 2006b; Nelson *et al.*, 2008). However, the boreal forest ecosystem is now going through profound changes due to human activities (Ostlund *et al.*, 1997; Chapin *et al.*, 2006b; Kasischke *et al.*, 2010; Boucher *et al.*, 2014; Gauthier *et al.*, 2015). The key question confronting forest managers is whether the process of change has reached a point at which the traditional goal of sustainability is simply not feasible. In such a situation, adaptability would be fundamental to sustaining various services of boreal forests.

Adaptive management is a process of managing natural resources in which the management itself is an experiment, and is an attractive approach particularly where large uncertainties exist (Stankey *et al.*, 2005). The desirability of adaptive management in natural resources has been recognized since the late 1970's (Holling, 1978; Walters, 1986; Lee, 1993), although examples of successful implementation of adaptive management are scarce (Stankey *et al.*, 2005). Adaptive management is apparently not easy to implement, but something like it is essential in dealing with the uncertainties of rapid global change. Preparing an effective framework for adaptive management is the essential first step in successful implementation.

Large-scale forest harvests have modified forest ecosystems in many parts of the boreal region. Canadian and Fennoscandia boreal forests have experienced extensive forest harvest management in the last century (Esseen *et al.*, 1997; Ostlund *et al.*, 1997; Gauthier *et al.*, 2015). To maximize production, short-rotation clearcutting followed by planting of crop trees has been applied widely, resulted in homogenous forest structures, in terms of species, age, and genetic diversity (Esseen *et al.*, 1997; Ostlund *et al.*, 1997). Further development and extraction of wood from boreal forests is likely due to increasing population (Gauthier *et al.*, 2015). Intensive wildfire suppression is another critical factor reducing biodiversity in these boreal forests (Esseen *et al.*, 1997). Compared to such intensively managed areas, Interior Alaska boreal forest is largely intact and management practices have been small-scale (Potapov *et al.*, 2008), providing a unique opportunity to identify largely natural ecological processes as a basis for adaptive management.

Climate change is one of the biggest challenges for adaptive forest management. North American boreal forest is primarily a stand replacement disturbance driven system (Rowe and Scotter, 1973; Foote, 1983; Chapin *et al.*, 2006a; Gauthier *et al.*, 2015), within which wildfire and insect damage or mortality are the dominant disturbances (Murphy *et al.*, 2000). Wildfires created diverse landscapes and stand structures of boreal forest in a resilient way for thousands of years (Johnstone *et al.*, 2010). However, the fire regime is changing due to both climate change, and human fire suppression as well as ignition (Murphy *et al.*, 2000; DeWilde and Chapin, 2006; Kasischke *et al.*, 2010). Climate change also affects the boreal forest ecosystem directly by affecting tree growth both positively and negatively, which is in the process of shifting forest composition (Barber *et al.*, 2000; Wilmking *et al.*, 2004; Juday *et al.*, 2015). The Alaska boreal region is experiencing a greater amount of warming than forest regions in lower latitude (increased 1.9 C° from 1949 to 2015 at Fairbanks; Chapin *et al.*, 2014). As a result, Alaska's boreal forest management faces the need to implement adaptive management sooner than elsewhere.

The goal of this study is to offer a general framework and options for adaptive forest harvest management through an assessment of data from the Alaska boreal forest. To achieve this goal, we compile and evaluate for the first time available management data (roads, timber harvest, wildland fire) over the past 40 years, the period during which silviculturally guided timber harvest has occurred, along with our sampling of tree regeneration in harvest units. Our objective is to offer an overview assessment of forest harvest management including (1) indicators of sustainable timber yield and management practices, (2) characteristics of forest harvest disturbance compared to wildfire, and (3) potential options relating to forest harvest and regeneration management approaches in light of climate change. While the subject of adaptation to climate change involves a vast amount of information in many different specialized fields, we believe it is useful to provide an initial synthesis of what existing information indicates for the key concerns of forest management in a place where climate change is an overriding issue.

5.4. Study Area and Field Sampling

Interior Alaska boreal region stretches from the Alaska Range in the south to the Brooks Range in the north, and Canadian border in the east to the Chukchi Sea in the west, covering about 47 million ha (Figure 5.1a). The principal long-term NWS First Order station for the study area is Fairbanks International Airport (1948-present; 133 m). The Fairbanks Airport climate record is a single point record taken on a grass surface near the runway (not forest). Due to the general lack of climate measurements in Alaska, it is traditionally used as one reference point in a number of analyses of climate trends and forest growth studies (Wilmking *et al.*, 2004; McGuire *et al.*, 2010; Juday and Alix, 2012). Mean annual temperature at Fairbanks Airport is -2 °C and annual precipitation of 270 mm, with extreme temperatures ranging from -50 °C to 35 °C. The period between freezing temperatures in the early 21st century is approximately 123 days at Fairbanks, an increase from 85 days in the early 20th century (Wendler and Shulski, 2009). However, climate in the region varies substantially according to factors such as elevation and aspect (Shulski and Wendler, 2007). Temperature inversion is a dominating factor that creates great temperature variability by elevation, especially in winter (Shulski and Wendler, 2007). Continuous, locally relevant climate data has been generated by downscaled climate data for the study area (SNAP, 2015).

Because of the extreme climate, species richness is low with six principal tree species, including white spruce (*Picea glauca* (Moench) Voss), Alaska birch (*Betula neoalaskana*), quaking aspen (*Populus tremuloides* (Michx)), and black spruce (*Picea mariana* (Mill.)), with a minor amount of balsam poplar (*Populus balsamifera*), and tamarack (*Larix laricina*; Labau and van Hees, 1990). The first three are the main commercial species. Permafrost covers a large area in Interior Alaska which is usually dominated by low-productivity black spruce forest and woodland. Although black spruce forest is largely underlain by permafrost, it is the most extensive forest cover type in Interior Alaska. However, here we focus on permafrost-free, productive forests that sustain most of the commercial harvest.

We used empirical data sampled in the Fairbanks and Kantishna management areas of Tanana Valley State Forest and state forest classified land located within Interior Alaska boreal region ("state forest lands"; Figure 5.1b). State forest lands covers 578,575 ha, of which ~75% is forested. We sampled 726 plots from 30 representative harvest units that were evenly distributed according to harvest types (16 clearcut and 14 partial cut units), site preparation methods (11 scarified and 19 unscarified units), reforestation techniques (16 planted and 14 naturally regenerated units), the year of harvest (1975-2004), size of harvest units, and the geographical location. In each plot, we sampled tree density, presence of understory vascular plants ($\leq$ 2 m), cover of each life form of understory vegetation (tree, shrub, herb, grass, sedge, Equisetum, fern, moss, lichen, and club moss), and moose browse density (number of stems that have been browsed by moose).

5.5. Ecological Functions

5.5.1. Biodiversity of Interior Alaska Boreal Forest

5.5.1.1. Landscape-level diversity

In Interior Alaska boreal forest stand-replacement wildfire creates disturbances with specific characteristics of size, pattern, severity, and total amount (Kasischke *et al.*, 2002; Kasischke *et al.*, 2010; Hollingsworth *et al.*, 2013). All of Alaska has been placed into fire management zones, and the greatest area (90%) falls within zones 3 and 4 ("modified" and "limited"), in which ignitions are not automatically suppressed. By contrast, most state forest lands (92%) fall within zones 1 and 2 ("critical" and "full") in which fire suppression occurs (Alaska Interagency Coordination Center, 2015). The overall mosaic of vegetation types and ages produced by the fire regime provides habitat for a wide range of wildlife species (Haggstrom and Kelleyhouse, 1996; Nelson *et al.*, 2008). Landscape patterns created by wildfire and forest harvest differ in some ways, such as size and spatial distribution. Wildfire creates burned patches across a full range of sizes (McRae *et al.*, 2001; Kasischke *et al.*, 2002; DeWilde and Chapin, 2006), whereas the size of harvest in Interior Alaska is generally small (Table 5.1). Size of wildfire varies from smaller than 1 ha to many 1,000s ha in Interior Alaska (DeWilde and Chapin, 2006) ("size" is the area within the fire perimeter, some area of which did not burn). The largest fire recorded is 0.55 million ha in 1950, and fires larger than 0.1 million ha occurred 44 times since 1943 (Alaska Interagency Coordination Center, 2015).

In contrast, size of harvest units in Interior Alaska have been small, with a median of 4.91 ha. Nearly 87% of harvest blocks were smaller than 20 ha (Table 5.1). The largest harvests were a few hundred hectares, and most of those were logged in 1970s when harvest area was likely overestimated in some of the large (non-clearcut) harvests (Doug Hanson, pers. comm., AKDOF, Aug. 2015). During the 1969-2012 time period, approximately 13,000 ha out of 1.2 million ha (1%) of land in the Tanana Valley was harvested (Morimoto, 2016), while approximately 16.5 million ha out of 47.1 million ha (35%) of total land of Interior Alaska region occurred within a fire perimeter (Alaska Interagency Coordination Center, 2015). A comparison of small (< 40 ha) fires versus cutting disturbances shows that the density (occurrence per unit of land area) of small forest harvest disturbances is greater than small fire disturbance. However, the total area disturbed by harvest is much smaller because of the lack of large-scale harvest (> 1000 ha; Table 5.1).

The large scale spatial distributions of wildfire and harvest are also different (McRae *et al.*, 2001). Wildfire starts anywhere from the Alaska Range to the Brooks Range in Interior Alaska (Alaska Interagency Coordination Center, 2015; Figure 5.2). Wildfire occurrence and expansion are principally affected by factors such as vegetation type, weather, and topography. In contrast, commercial forest harvesting in Interior Alaska is concentrated in small area in the Tanana Valley close to Fairbanks, the second largest city in Alaska (Figure 5.1). Most harvests are within a small distance from major highways near Fairbanks, or rivers which freeze sufficiently to support vehicles in winter (Figure 5.3; Morimoto *et al.*, 2016) because of a limited road system (Wurtz *et al.*, 2006). In addition, harvest has mainly occurred in mature white spruce forest due to its greater economic value than other local species (Wurtz *et al.*, 2006).

However, during the period that fire records have been maintained or reconstructed (1943 onward), the fire regime has been shifting because of human activities, including human ignited fires and fire suppression (Kasischke *et al.*, 2010). Lightning was the major cause of wildfire in the entire data period, but human-caused fire has increased substantially with time (62% of fires but 4.6% of area burned; DeWilde and Chapin, 2006). Human-caused fires are generally smaller than lightning-caused fires primarily because human-caused fires often occur in the area of strict suppression. Most (89%) of the smallest fires (< 0.4 ha) were human caused, and 78% of all human-caused fires were smaller than 0.4 ha during 1986-2000 (DeWilde and Chapin, 2006). Fires ignited by lightning that subsequently grew to no more than 0.4 ha occurred mostly in the "critical" fire suppression zone. Large-scale wildfires (> 400 ha), from any cause were more common in remote areas where fires are not automatically suppressed by fire management policy (DeWilde and Chapin, 2006; Figure 5.2).

If the fire regime in areas under forest management in the future were similar to the past 70 years, areas with a strict suppression policy would experience fewer large-scale fires than before suppression began, resulting in increased average stand ages. Some mature forests which have passed their most productive stage begin to lose ecological and economic values, and add a higher risk of future large-scale fires because of higher flammability (Chapin *et al.*, 2003).This projected increase in older forest composition would also reduce the availability of habitats for early successional wildlife species. Forest harvest can produce the younger forest age classes that would otherwise decrease in areas of fire suppression. Both old-growth forests, which are essential for specialized boreal species, and landscapes with diverse forest age structures are essential to sustain the full diversity of wildlife (Nelson *et al.*, 2008). Both fire suppression and forest harvest can to a certain degree create or sustain the required age structures.

Landscape-scale forest age class and type diversity contributes to maintaining diverse wildlife species in Interior Alaska (Nelson *et al.*, 2008). Moose, one of the most important subsistence species in Interior Alaska, use both early- and late-successional forests for different purposes (MacCracken and Viereck, 1990; Balsom *et al.*, 1996; Nelson *et al.*, 2008; Lord and Kielland, 2015). Moose use recently burned forest (up to a few decades post-fire) as a feeding habitat because of the higher food availability (MacCracken and Viereck, 1990; Nelson *et al.*, 2008; Lord and Kielland, 2015). But moose also select and use mature spruce stands, especially in winter because of the shallow snow cover (Balsom *et al.*, 1996), greater seasonal browse availability (Balsom *et al.*, 1996), protection from heat and cold (Balsom *et al.*, 1996), and cover from predators (Balsom *et al.*, 1996). Despite the abundance of browse in young post-fire sites, moose density decreases with distance into burned stand, largely because of the lack of mature forest predator cover (Weixelman *et al.*, 1997). As a result, a mosaic of various age classes and forest types is important in sustaining a moose population on a landscape.

We tested for differences in post-harvest moose browse density in our study area for a number of management situations, including time since harvest, management practices (clearcutting vs. partial cutting, no treatment vs. site preparation, and natural regeneration vs. planting white spruce), size of harvest, and distance from edge (Appendix 5.1). We found that browse density tended to decrease with increased time since harvest (Appendix 5.1), which is consistent with post-fire moose behavior (Nelson *et al.*, 2008). However, browse occurrence increased with distance from edge and size of harvest (Appendix 5.1), which is inconsistent with previous findings (Weixelman *et al.*, 1997). We believe this effect is due to the very small-scale of harvest within the landscapes we studied which is associated with a shading effect near the harvest perimeter. The harvest units we sampled ranged from 1.4 – 30.3 ha in size, which means that even the center of the largest unit was within the preferred edge distance that moose seek. Further study of the effect of forest harvest on moose is necessary, especially incorporating a spatial component and higher sampling intensity.

Many other wildlife species in Interior Alaska require specific types of habitat (Magoun and Dean, 2000; Nelson *et al.*, 2008). For example, caribou depend heavily on the lichens in mature spruce-lichen forest as a source of food (Joly *et al.*, 2003). The boreal forest is distinctive among the major ecological regions of the earth for being conifer dominated (Juday, 1997). Older conifer forests on more productive sites are the source of a significant share of biodiversity conservation issues across the boreal region for several reasons. Such stands are particularly rich in canopy lichens, mosses, and bryophytes.

Old conifer forests are also rich in fungi responsible for decomposing wood and in specialized wood-boring and foliage-consuming insects, which are consumed by woodpeckers and other cavity nesting animals and insectivorous songbirds (Esseen *et al.*, 1992; Berg *et al.*, 1994). These stands usually support the highest wood product values and are often targeted for early harvest in a forest management program. In boreal Alaska, the older white spruce type has been the focus of harvest (Wurtz *et al.*, 2006; Morimoto, 2016). As a result, harvest can systematically deplete important forest structures, particularly older (productive) white spruce types that are increasingly limiting habitats, unless management plans and practices incorporate specific goals to maintain these features.

5.5.1.2. Stand-level diversity

Stand-level biodiversity is promoted by heterogeneous forest structures, which are often the product of wildfire in early-successional stands. Coarse woody debris (CWD), such as snags and fallen trees, have been identified as one of the critical components for sustainable boreal forest management (Magoun and Dean, 2000). The amount of CWD increases considerably after natural disturbance (Brassard and Chen, 2006). CWD left after disturbance provides habitat for a number of species, specifically for birds that use wood cavities for nesting and roosting (Haggstrom and Kelleyhouse, 1996; Hagan and Grove, 1999). CWD also provides various types of soil substrate, resulting in a spatially heterogeneous vegetation community (Lee and Sturgess, 2001). Finally, CWD plays an essential role in nutrient cycling (Magoun and Dean, 2000). Forest harvesting, in general, reduces the amount and types of CWD compared to wildfire (Pedlar *et al.*, 2002; Brassard and Chen, 2008). CWD left after fire primarily consists of standing dead trees of all sizes, while CWD left after harvest is mostly made up of small logs and stumps (Pedlar *et al.*, 2002). Moreover, forest harvesting leaves more CWD of hardwood species than conifers, because the greater economic value of conifers is a greater incentive for removal and utilization (Brassard and Chen, 2008). Variable retention harvest increases use of the harvested area by old-growth forest bird species compared to complete tree removal (Schieck and Song, 2006). Retaining at least some elements of CWD from the full range of tree sizes and species on harvested sites provides both wood harvest and specialized wildlife habitats, although it can potentially decrease revenue from harvest. Few studies of CWD following either fire or harvest have been conducted in Interior Alaska (Paragi and Haggstrom, 2005; Alexander *et al.*, 2012). In order to manage for such multiple simultaneous goals for CWD, it is essential to understand the amount, type, and distribution of CWD and their dynamics, and the effects of the presence or absence of CWD on forest ecosystems, including both plants and wildlife.

Understory vegetation is another component of diversity in the boreal forest ecosystem. Understory species regulate multiple functions in boreal forests, such as tree regeneration, soil nutrient cycling, and wildfire frequency (Nilsson and Wardle, 2005; Jandt, 2009; Boan *et al.*, 2011). Interior Alaska boreal forest is known for supporting a low plant species diversity (Waide *et al.*, 1999). But in general, understory vegetation has not been well studied in boreal regions (Nilsson and Wardle, 2005). Diversity of understory vegetation following disturbance is influenced largely by the amount of residual vegetation and the depth of organic layer (Haeussler *et al.*, 2002; Rees and Juday, 2002; Haeussler and Bergeron, 2004). When disturbance removes most vegetation, a small number of pioneer species dominate the stand, and species diversity decreases. In Interior Alaska, site preparation is often applied to reduce the cover of *Calamagrostis canadensis* (Wurtz and Zasada, 2001; Youngblood *et al.*, 2011) which is a major problem for post-harvest tree regeneration in Interior Alaska (Lieffers *et al.*, 1993). However, our data indicated that operational site preparation area actually increased *Calamagrostis canadensis* and decreased diversity (Figure 5.5ab). This indicates that site preparation should be applied with caution and good knowledge of the likely effects.

5.5.2. Successional Pathway

The stand initiation stage (Oliver, 2007) following disturbance decisively influences future forest structure and composition, particularly in the boreal forest which usually originates from large scale disturbances (Rowe and Scotter, 1973; Chapin *et al.*, 2006a). Long-term monitoring of post-harvest regeneration is still necessary to identify the entire successional pathway, but identifying early post-disturbance regeneration provides a useful early look at likely boundaries of future forest development. In Interior Alaska boreal forest, depth of organic layer is an essential factor affecting the initial regeneration trajectory (Johnstone *et al.*, 2004; Shenoy *et al.*, 2011).

Fire in white spruce or hardwood stands on permafrost-free sites often results in the consumption of some portion of the surface organic layer. Light consumption of the surface organic layer allows regeneration of most of the original species which regenerate asexually. In contrast, heavy consumption of the organic layer or exposure of the mineral soil promotes the establishment of new vegetation from seeds. A mosaic of high and low fire severity conditions within the burn perimeter allows succession to begin with a wide variety of species, both pioneer and residual species (Van Cleve *et al.*, 1996).

Spruce and hardwood tree species both become established during this early post-fire phase, but hardwoods have a greater chance of early dominance because of their reproductive ecology. While fire often kills many or most the of aboveground stems of birch and aspen, regenerating ramets (stems of the genetically same individual tree or "clone") start growth in the immediate post-fire environment with a largely intact root system of a mature clone. These ramets can achieve considerable height growth within a year or two (MacCracken and Viereck, 1990). However, new hardwood stems are the preferred browse of moose, and a major challenge for these stems is to escape from the browse height zone. White spruce regenerate almost exclusively from seed (Nienstaedt and Zasada, 1990) unlike birch and aspen which regenerate both sexually and asexually (Perala, 1990; Safford *et al.*, 1990). In addition, white spruce produce a large seed crop only about every 11 years (Roland *et al.*, 2014) and most seeds fall within 100-150 m from the seed source (Youngblood and Max, 1992), so the species is frequently limited by seed production timing and seed dispersal distance. If a large seed crop occurs, white spruce can regenerate within a few years after fire (Purdy *et al.*, 2002) but white spruce early growth is generally slower than birch and aspen (Greene *et al.*, 1999).

Spruce is seldom browsed by moose in Interior Alaska (Nienstaedt and Zasada, 1990), although young spruce can be damaged by moose scent-marking (Bowyer *et al.*, 1994). However, white spruce are browsed by snowshoe hares (*Lepus americanus*), especially in winter (Wolff, 1978). The snowshoe hare is a keystone species in the boreal forest, dominating the herbivore biomass, and driving many of the ecological changes in the forest (Krebs *et al.*, 2001). The abundance of snowshoe hare fluctuate in approximately 10 year cycles (Krebs *et al.*, 2014).

As a result, white spruce regeneration and growth is affected significantly by snowshoe hare abundance (Angell and Kielland, 2009), and the effect is magnified in years of peak hare abundance (Olnes and Keilland, submitted). Hare browsing effects are restricted to ground level up to a height of 1.5 to 2.0 m, and so primarily kill or retard spruce in the earliest seedling stages of establishment and growth. Above this height, repeated clipping of spruce terminal shoots by squirrels (Klugh, 1927; Smith, 1968; Whitaker and Hamilton, 1998) can also prevent or reverse spruce height dominance in its competition with hardwoods.

Well-positioned spruce can assume canopy dominance from their earliest years of establishment. After several years, birch and aspen outgrow herbs, grass, and shrubs, and tend to dominate many stands, while white spruce seedlings that do not achieve open canopy position grow slowly under hardwood canopy. Under such competition, white spruce generally require several decades, up to a century, to enter into the canopy (Youngblood, 1995). Hardwoods experience a rapid self-thinning in the early decades following fire disturbance (Perala, 1990; Safford *et al.*, 1990).

Our data indicate that post-harvest natural regeneration, in general, follows a similar pattern to post-fire succession (Figure 5.6). We found that stands dominated by white spruce before harvest had become mixed spruce and hardwood forest after 40 years (Figure 5.6). Birch and aspen dominate logged stands within 10 years, and then start self-thinning about 10-20 years after harvest (Figure 5.6). White spruce natural regeneration appears to continue to accumulate (or first become visible) for a few decades (Figure 5.6), even though previously white spruce recruitment was generally believed to be limited to only a few years after harvest (Thompson, 2005). Overall density of white spruce and birch became similar by about 40 years after harvest, but white spruce stems are smaller in diameter compared to birch, due to their slower rate of growth (Figure 5.6).

The successional pathway of understory vegetation after white spruce harvest, however, is different than in succession following fire in white spruce forest (Rees and Juday, 2002). Post-fire succession in central Interior Alaska starts with specialized early-successional species, and the species turnover rate is higher for several decades than in succession following logging. Succession following disturbance by logging alone (no subsequent fire or site preparation) starts with a species assemblage more similar to old-growth forest. On logged sites, species turn over at a lower rate than on burned sites, due both to the lack of occurrence of a unique set of post-fire species, and to a thicker remaining organic layer that sustains a mature forest soil environment in the early years (Rees and Juday, 2002).

5.6. Forest Harvest Management and Sustained Yield

Interior Alaska experienced intensive, but highly localized forest harvesting in the late 19th century to early 20th century as a result of development of mining and urban areas (Roessler, 1997; Wurtz *et al.*, 2006). Purposeful and silviculturally based forest management only began in boreal Alaska after statehood in 1959 and the transfer of land entitlements to the state government, Alaska Native corporations, and borough governments. Generally, databases and records of forest management activities begin only in the early 1970s. As a consequence, only recently has it been possible to empirically assess the experience and outcomes of Alaska boreal forest management and consider some of the traditional issues and indicators of sustained yield. For the last several decades, the silviculturally planned harvest activity has been small-scale because of the low demand, limited road access, and the long distance from major markets

(Wurtz *et al.*, 2006). During this time, wood products were harvested continuously as demand increased. Major product included large white spruce for log cabins, local sawtimber, export logs primarily to Asian market in the late 1990s, and all species for fuelwood. Moreover, the demand for wood biomass for energy generation is increasing (Fresco and Chapin, 2009).

Currently, forest management in central Interior Alaska is restricted to small-scale, low-input management (Morimoto, 2016). Annual harvest area and volume are far below annual allowable cut (white spruce = 11%, birch = 1%, aspen = 0.2%; Morimoto, 2016), suggesting harvest can be significantly expanded sustainably. In Interior Alaska, clearcutting, or species and/or diameter selection cut have been the major harvesting methods (Alaska Division of Forestry, 2013; Morimoto, 2016). Following harvest, mechanical site preparation and/or planting of white spruce seedlings are applied at limited scale (Morimoto, 2016).

Clearcutting is widely used in boreal forests, and is effective when applied with caution. However, clearcutting can produce undesirable ecological outcome if it is applied without attention to the landscape context (Timoney and Peterson, 1996; Ostlund *et al.*, 1997; Lofman and Kouki, 2001). In Interior Alaska, some studies comparing clearcutting to partial cutting found no differences, or even some positive effects of clearcutting on post-harvest regeneration (Youngblood and Zasada, 1991; Wurtz and Zasada, 2001; Morimoto, 2016). Silviculturally planned clearcutting in central Interior Alaska has been small-scale, and did not create large homogenous landscape or issues with natural regeneration caused by seed dispersal ability (Morimoto, 2016) unlike Canada and Fennoscandia boreal forests, which have experienced large-scale clearcutting with short rotation periods (Ostlund *et al.*, 1997; Lofman and Kouki, 2001; Boucher *et al.*, 2014).

Site preparation appears to have the greatest effect on post-harvest regeneration in North American boreal forest (Youngblood and Zasada, 1991; Wurtz and Zasada, 2001; Calogeropoulos *et al.*, 2004; Boateng *et al.*, 2009). Most studies from Interior Alaska have concluded that site preparation caused an increase in post-harvest regeneration by exposing mineral soil (Youngblood and Zasada, 1991; Wurtz and Zasada, 2001). However, following a major white spruce seed crop, site preparation can result in overstocking (Wurtz and Zasada, 2001; Morimoto, 2016).

Although planting white spruce seedlings results in greater numbers of white spruce in a harvest area in the early stage of regeneration, the overall effect of planting on spruce density and total basal area is limited (Morimoto, 2016; Morimoto *et al.*, 2016). Planting seedlings is the most expensive post-harvest management practice, and the selection of seed stock can modify and/or decrease genetic diversity. In sum, harvest and post-harvest practices can affect regeneration outcome both positively and negatively, and the management practices that are applied need to be selected according to goals and specific situations. However, past management experience may not be relevant if the environment in which it occurred changes beyond the level that generated those outcomes.

5.7. The Effects of Climate Change

High latitude regions such as Alaska are experiencing the greatest temperature increases in the recent climate warming (Hartmann *et al.*, 2013; Chapin *et al.*, 2014). As a result, climate change is one of the major challenges for sustainable forest management. Climate warming is causing changes in the physical environment, including longer growth seasons and warming or thawing permafrost (Hinzman *et al.*, 2005). Temperature increases have begun affecting Interior

Alaska boreal forest both directly and indirectly, including changing tree growth (Barber *et al.*, 2000; McGuire *et al.*, 2010; Juday *et al.*, 2015), advancing tree lines into tundra (Wilmking *et al.*, 2004), warming or thawing permafrost, and modifying wildfire behaviors (Johnstone *et al.*, 2010). Studies of climate warming in relation to tree growth have focused on mature crop trees (Barber *et al.*, 2004; Wilmking *et al.*, 2004; McGuire *et al.*, 2010). However, climate sensitivity is dependent on age, species, and site. In particular, young tree regeneration apparently responds to climate warming differently than mature stands (Szeicz and Macdonald, 1994; Mamet and Kershaw, 2013), and this difference may be due to the different ratio of root to above-ground biomass in young versus old trees. In Interior Alaska drought stress has reduced growth of mature white spruce to near survival limits (Barber *et al.*, 2000; Wilmking *et al.*, 2004; McGuire *et al.*, 2010; Beck *et al.*, 2011). In western Alaska closer to the Bering Sea, temperatures have increased from barely suitable to near the optimum for white spruce, and trees on formerly marginal sites now are growing at the highest rate of all floodplain populations (Juday *et al.*, 2015). This overall pattern of growth increases and decreases suggests biome shift (Murphy *et al.*, 2012).

However, to date the effects of climate warming in central Interior Alaska on early regeneration appear to be minor, based on adequate levels of tree density observed up to 40 years following harvest (Morimoto *et al.*, 2016). Post-harvest regeneration has developed entirely within the warmer conditions that have prevailed in Alaska since the climate regime shift of the mid-1970s (Barber *et al.*, 2004), unlike mature 100-200 year old trees that are the basis for findings of temperature induced growth stress (Barber *et al.*, 2000). As a result, the regeneration could have had the opportunity to compete and adjust under the new climate regime. By contrast, the effects of climate warming appear in the later phase of forest succession, when trees have grown lager, root biomass in relation to leaf biomass is lower, and the efficiency of water translocation has decreased (Szeicz and Macdonald, 1994). The effects of climate warming may appear suddenly once a temperature threshold is reached (Costantini *et al.*, 2014), suggesting large scale tree mortality from climate stress alone – not induced by biological agents such as insects - is likely in areas that experience temperatures at threshold limits (Allen *et al.*, 2015). A scenario study of post-harvest regeneration in central Interior Alaska showed that the success of post-harvest regeneration would decrease under a modest climate scenario (IPCC A2 scenario), and the effects would appear more profound on birch and aspen (Morimoto, 2016).

Another profound effect of climate change is a changing fire regime because of the warmer and drier climate (Chapin *et al.*, 2008). Larger, more severe, and more frequent fires modify successional trajectories of Interior Alaska boreal forest (Johnstone *et al.*, 2010). The major regeneration pathway following fire in Alaska's black spruce stands has been the reestablishment of pre-fire vegetation (Johnstone and Kasischke, 2005). The new fire regime more frequently causes deep consumption of the soil organic layer, promoting colonization of pioneer species, rather than self-replacement of black spruce. White spruce faces also regeneration challenges after large and frequent fires because of its reproductive ecology and slower growth compared to hardwoods (Greene *et al.*, 1999). Large and intense fire eliminate white spruce seed sources, resulting in failure of white spruce regeneration (Timoney and Peterson, 1996). In addition, with more frequent burning, white spruce seed crop years may not align closely with fire disturbance, reducing the probability or density of establishment because of poor seedbed receptivity (Packee, 1990). Finally, if two fires occur without adequate time after the first for spruce to reach reproductive maturity, the species will be locally eliminated in the succession that follows the second due to the lack of seed source (Brown and Johnstone, 2012).

In contrast, hardwood species have lighter seeds and regenerate both sexually and asexually (Perala, 1990; Safford *et al.*, 1990), so they face fewer constraints on regeneration in an altered fire regime. Eventually, the intensified fire regime is likely to produce negative feedbacks to fire. An intensified fire regime is projected to convert landscapes dominated by evergreen conifers to hardwood-dominated landscapes with lower flammability (Rupp *et al.*, 2000; Barrett *et al.*, 2011). However, severe climate warming may make even hardwoods flammable, and Interior Alaska boreal forest may be converting to non-forest with completely different fire regimes (Johnstone *et al.*, 2011).

The intensifying forest disturbance regime from fire and insects associated with increasing temperatures is likely to convert a much greater amount of old-growth to early successional stands than forest management, even in the area where fire suppression has been relatively effective. Fire and insect disturbance as well as the indirect effects of climate warming, often involve mature conifer types, and reduce not only the current inventory of these stands, but the prospects for their replacement on the sites where they have typically occurred in the past. As a result, a timber production system based on white spruce is likely to face sustained yield challenges unless intensive practices, such as fire protection and repeated planting, are applied.

5.8. Implication for Adaptive Forest Management in Interior Alaska

We used 40 years of forest harvest management practices as a basis for the essential parts of adaptive management: monitoring, evaluating, and adjusting (Figure 5.7). Continued monitoring and evaluation is essential for successful adaptive management, particularly because of the short history of systematic forest harvest management in the study area. Other factors need to be considered for successful implement of adaptive management, particularly economic factors. Forest harvest management in central Interior Alaska currently produces marginal or no profit, making expansion or modification of management programs that add cost mostly impractical. Controlling the cost of management practices, adjusting to market demand, and correctly anticipating expected profit will be essential to implement forest harvest management. However, this study provides the basis to build adaptive forest management for the first time in boreal Alaska, which requires it sooner than elsewhere due to the rapid climate warming.

The current small-scale, low-input management appears to have limited adverse effects on the forest ecosystem, and would represent sustainable forest management under stable environmental conditions. In the area where fire has been suppressed strictly, forests continue to age. In these areas, forest harvesting can be used to improve forest health, recoup economic values, and reduce fire risks in the areas near community and roads. However, fire suppression is not likely to be as effective in the future, as fire intensity, severity, and frequency increase due to climate warming. It should also be noted that the current success of post-harvest regeneration is partly a result of very small areas of harvest in a vast and relatively intact forest, and the legacy effects of a climate regime that is increasingly not present and not likely to persist. Successful management in the future will require monitoring and adjustment as climate continues to change, the total managed area expands, and second harvest begins in managed forest.

In order to be successful, any forest management program must align specific stand-level practices to the overall goals of management (Oliver and Larson, 1996; Smith *et al.*, 1997). The experience of the past 40 years of forest management in central Interior Alaska provides the opportunity to describe and evaluate this decision process for harvest and regeneration management of the mature white spruce type. The approach can be depicted as a flow chart of management decisions, actions, and ecological factors - including in particular the timing of white spruce seed crops (Figure 5.8). It is important to note that this management decision process applies only to white spruce harvest and considers only within-stand outcomes, but not between-stand influences (spatial component). It also assumes that climate/environmental conditions roughly similar to the historical period will persist over the projected forest rotation.

In order to maximize post-harvest regeneration, cost efficiency, and structural diversity, clearcutting with reserves appears to be the most effective harvest method (Figure 5.8). Retention of various sizes and species of residual trees can increase structural diversity, even though it can reduce harvest revenues. Following harvest, if a large white spruce seed crop is present or expected, neither site preparation nor planting seedlings is necessary, because either would likely result in overstocking (Figure 5.8). Seed production in white spruce can be estimated by the previous year's seed production and visual inspection of bud primordia (Lamontagne and Boutin, 2007; Gartner *et al.*, 2011). Foresters should check for the indicators of a white spruce seed crop shortly before and after harvest and then make appropriate adjustments. Relying on natural regeneration has an obvious advantage of cost saving and also other advantages, particularly retaining native genetic diversity on managed sites.

However, if a white spruce seed crop is not present or expected, specific post-harvest reforestation practices may be required to achieve a desired management goal. First, if large dimension white spruce production is a critical management goal, planting white spruce seedlings may be desirable in order to obtain white spruce trees that achieve and sustain canopy dominance from the earliest possible time following harvest (Figure 5.8). Second, if wood biomass production is the management goal, target species need to be specified. When white spruce is the target species, planting seedlings might be necessary (Figure 5.8). In contrast, where hardwood material can be harvested for wood biomass products, short-rotation forest management would be possible without the strenuous efforts often needed to establish white spruce (Figure 5.8). In any case, site preparation following harvest will enhance seedbed quality for tree establishment and growth (Figure 5.8).

If a management goal is to sustain habitat diversity for a full range of boreal species, the specific forest type to be developed needs to be identified. When a white spruce component is to be sustained, planting seedlings may be necessary or desirable (Figure 5.8). When producing an abundant early successional hardwood component is the goal, natural regeneration would very likely be adequate (Figure 5.8). In both cases, the severity of ground disturbance needs to be kept low/intermediate to avoid extensive dominance by pioneer species and to maximize diversity of understory vegetation.

Despite the complex ecological processes and interactions in the boreal forest, the limited number of species, and the strong controls exerted by key elements in the system have tended to produce outcomes that are reasonably predictable (Morimoto, 2016). However, the highly likely increase of global mean surface temperature by the end of the 21st century, although it will be substantially affected by assumptions about future emissions, would exceed 1°C under all but the lowest emission scenarios, and the warming in the Arctic will be greater than the global mean (IPCC, 2014). If so, climate warming is likely to start causing failure of post-harvest regeneration on vulnerable warm, low elevation sites in the near future once the temperature increases reach a threshold level (Morimoto, 2016). As a result, forest management needs to be adaptive to the change.

We identify three main adaptive boreal forest management options under a regime of increasing temperatures: (1) maintaining current species, (2) maintaining a forest landscape of any type, and (3) allowing biome shift from forest to other biome types (Figure 5.9). In addition, we identify research need for the adaptive management approaches.

First, the key to maintaining current species will be to identify new sites and regions that will experience sustained or enhanced growth potential under increased temperatures. Boreal Alaska is made up of diverse landscapes, regional climate gradients, and includes areas of complex topography. Examples of sites with enhanced forest potential with continued temperature increases include higher elevations (Wilmking *et al.*, 2004), aspects with less south exposure, and locations in western Alaska (e.g. Juday *et al.*, 2015). A number of these areas of enhanced forest potential are not near current infrastructure, and essentially do not have a history of forest management. As a result, monitoring growth and health of post-harvest regeneration will be critical (Figure 5.9).

If maintaining current species in areas where climate is already, or soon to be, beyond optimal for tree growth (Juday *et al.*, 2015) is the goal, adaptive migration of genetically diverse populations such as happened in the past (Roberts and Hamann, 2015) is necessary. In any event, forest management will need to incorporate genetic studies (e.g. Alden, 1991) to a degree well beyond what has occurred to date in order to identify the specific gene types best adapted to the new and emerging environmental conditions.

If maintaining a forest landscape of any type is a future goal, then conceivably the introduction of species that grow better under the new, warmer climate regime might be an option (Hagman, 1993). Introduction of exotic, non-native species poses a number of well-recognized risks (Pimentel *et al.*, 2000). However the concept of "non-native" itself may need to be reconsidered, at least in the context of managed landscapes, under the magnitude of climate change now emerging in the far north. Despite the generally low species richness of the far north, nearly 30 tree species capable of stand dominance are adapted to extreme cold temperatures and high latitude locations, 15 of which are native North American species (Nikolov and Helmisaari, 1992). Native North American boreal tree species have migrated north and south across much of the continent in response to past climate changes (Anderson *et al.*, 2006). A conservative management approach would be to begin now to examine the genetic adaptability of North American tree species populations that, under continued warming, would arrive in northern Alaska simply given enough time (Figure 5.9). A further step would be to screen the most adaptive species of any origin while carefully examining invasive potential (Alden, 2006).

Finally, biome conversion of boreal forest to shrubland or grassland (Hogg and Hurdle, 1995) might be an option in the most vulnerable areas to climate warming. Opportunities on the converted lands need to be assessed, such as new products and potential subsistence wildlife species. In Interior Alaska, Wood Bison have been reintroduced (Alaska Wood Bison Management Planning Team, 2015) as one part of a comprehensive conservation recovery strategy (e.g. Sanderson *et al.*, 2008) that will very likely produce harvestable products.

Forest management, by its very nature, has always confronted uncertainties about the future. In many ways the forestry profession has developed as a response to the need to make decisions, provide for human needs from forest lands, and sustain the forest ecosystem in the face of uncertainty (e.g. Oliver and Larson 1996; Smith *et al.* 1997). Climate change as an issue confronting forest management has evolved from a distant prospect to an unfolding reality as it is being experienced in boreal Alaska. In its brief history, professional forest management in Interior Alaska has developed and has been required to adapt to the particular circumstances it faced. We have offered here a framework to build on the knowledge and practices of the past, meet the needs and challenges of today and demonstrate an approach to prepare for the challenges of the future in one of the most rapidly changing forest regions of the world.

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5.11. Table

Table 5.1 Size distribution of harvest blocks (continuous area of harvest in a given year).

Area (ha)	Density of harvest blocks ($[\text{million ha}]^{-1}[\text{decade}]^{-1}$)
0-10	172.7
10-20	32.9
20-30	16.5
30-40	6.7
40-50	2.7
50-60	1.9
60-70	0.2
70-80	0.2
80-90	1.0
90-100	0.2
100-200	1.5
200-300	0.6
300-400	0.0
400-500	0.2
500-600	0.0
600-700	0.4

5.12. Figures

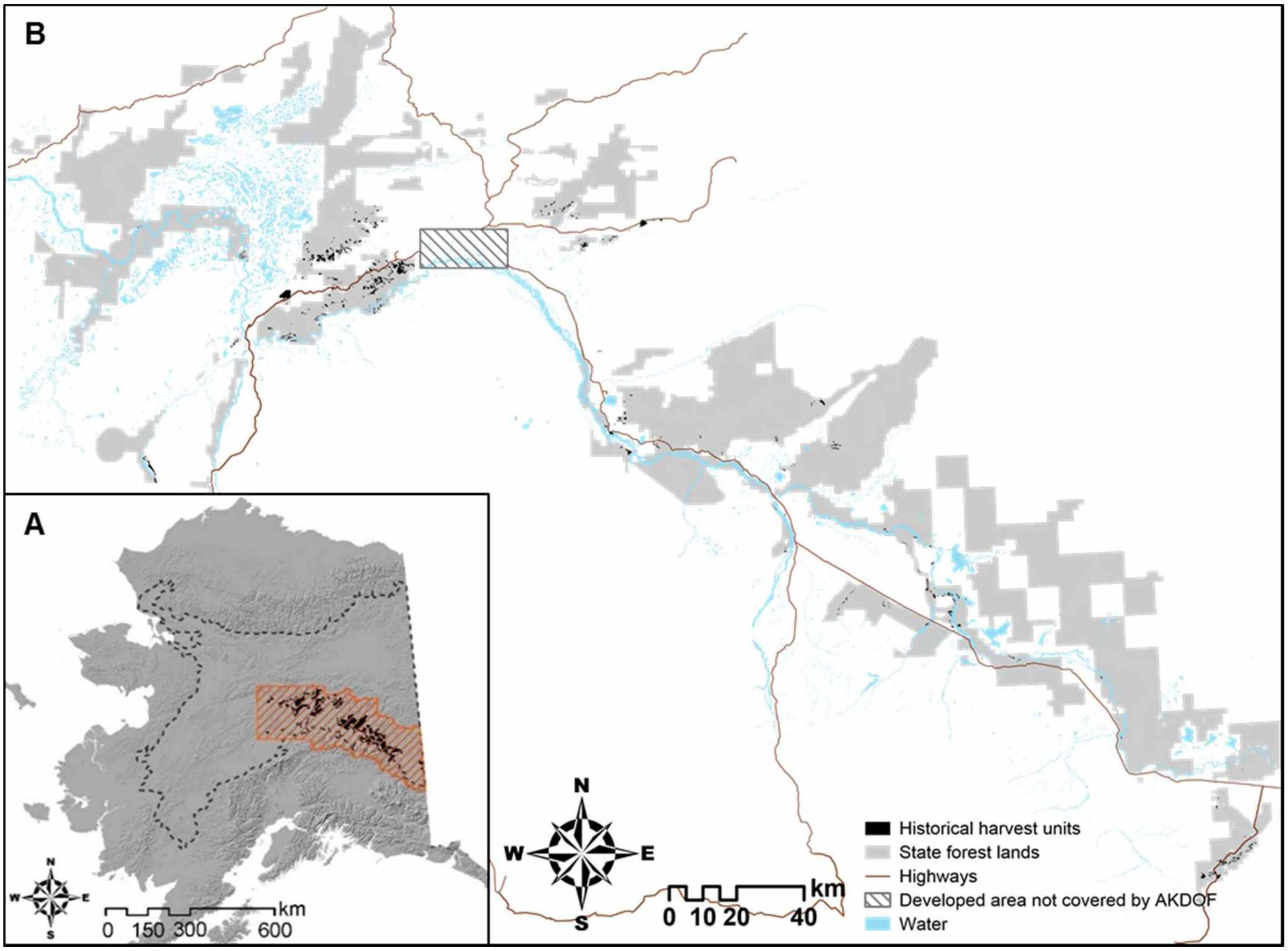


Figure 5.1 Map of study area. (a) Study area is within the Tanana Valley (orange boundary) in Interior Alaska boreal region (dashed area). (b) Most historical forest harvests occurred within the Tanana Valley State Forest and state forest classified land (state forest lands), and a few are in public lands, including Fairbanks North Star Borough, Native Allotments, and Native Corporation lands. There are other forest harvests in different ownerships which were not included in this study because of the relatively small scale operations.

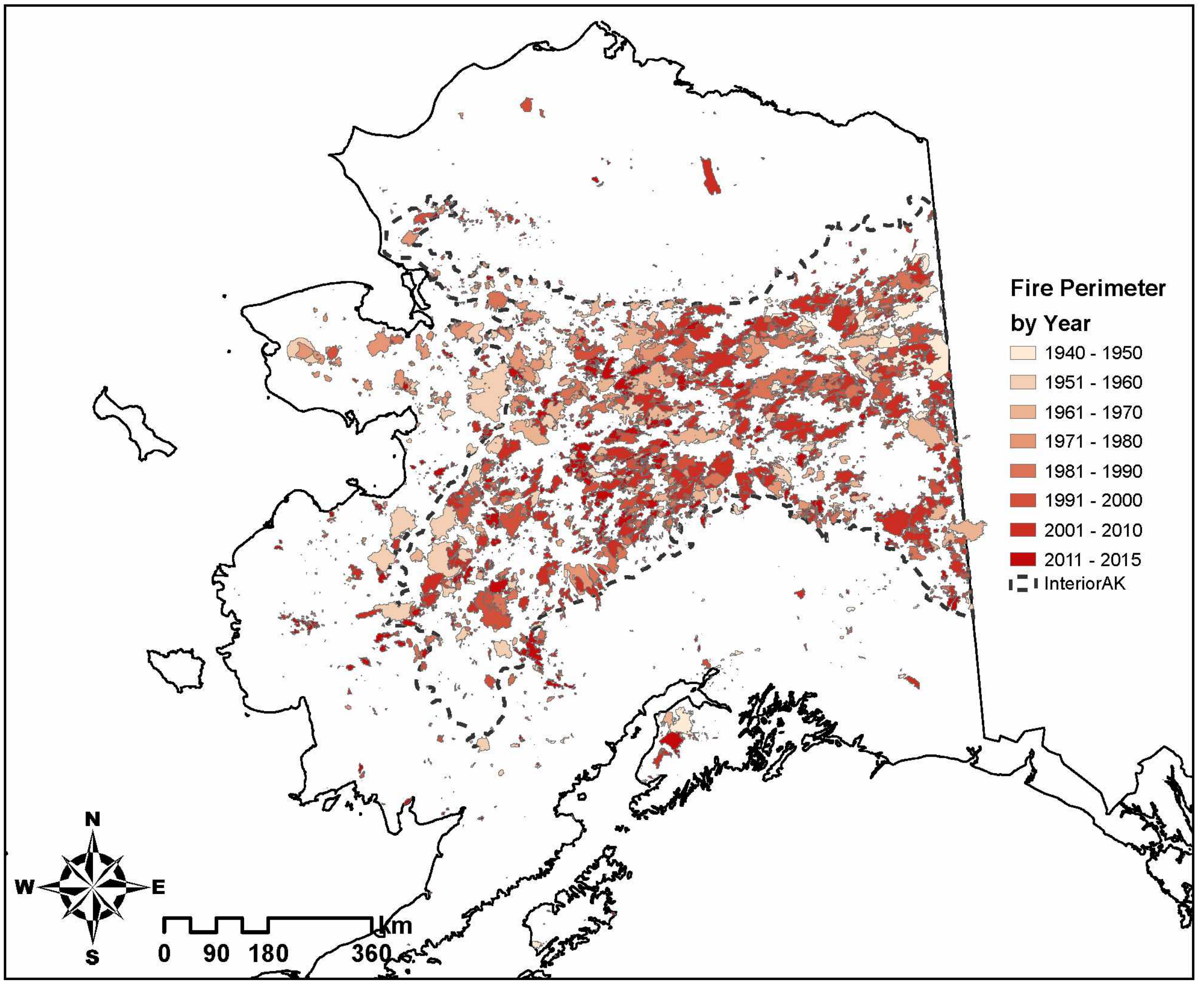


Figure 5.2 Map of perimeters of historical wildfires in Alaska from 1940 to 2015 (Alaska Interagency Coordination Center, 2015).

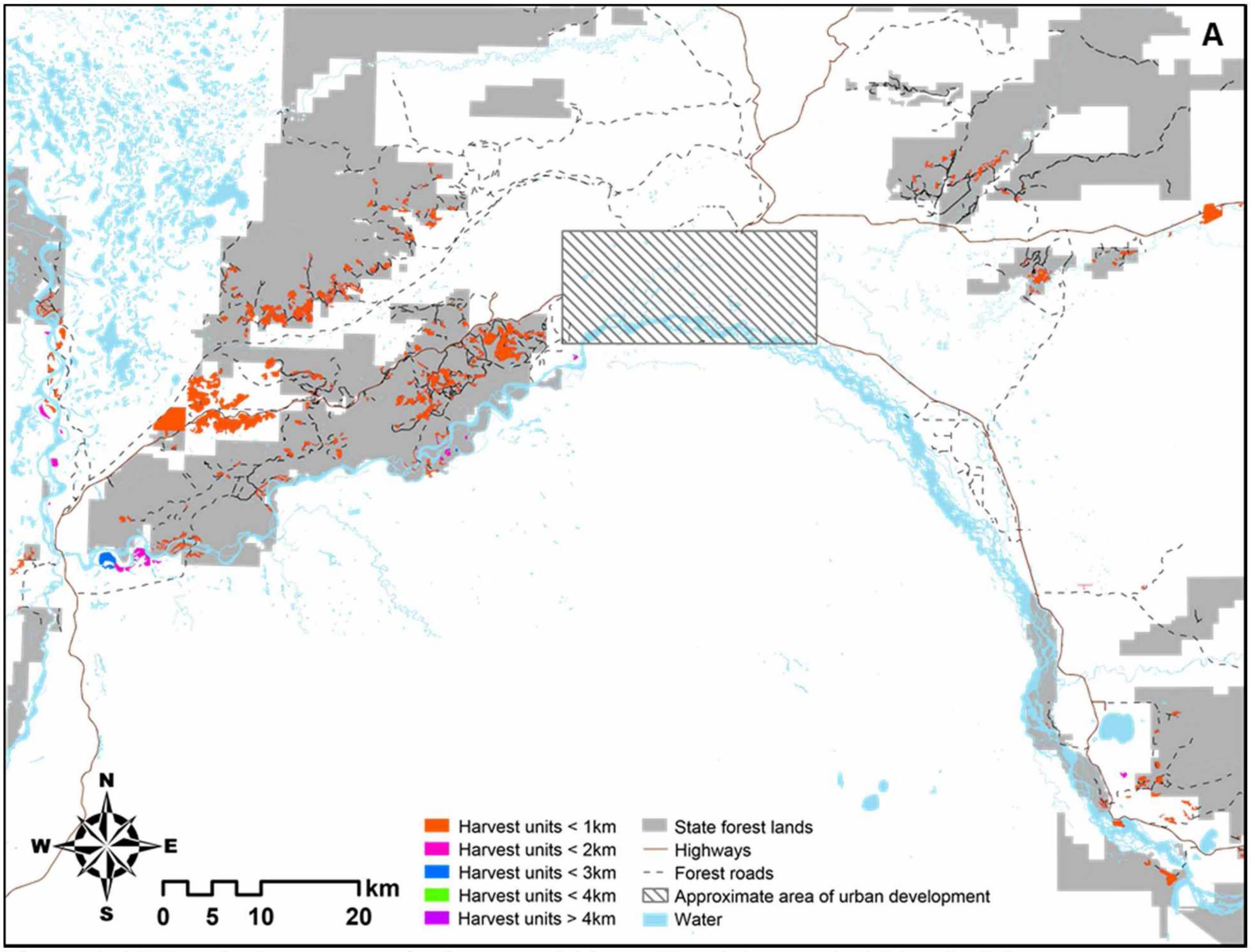


Figure 5.3 Historical harvest units in part of (a) the Kantishna and Fairbanks Management areas, and (b) the Delta and Tok Management areas.

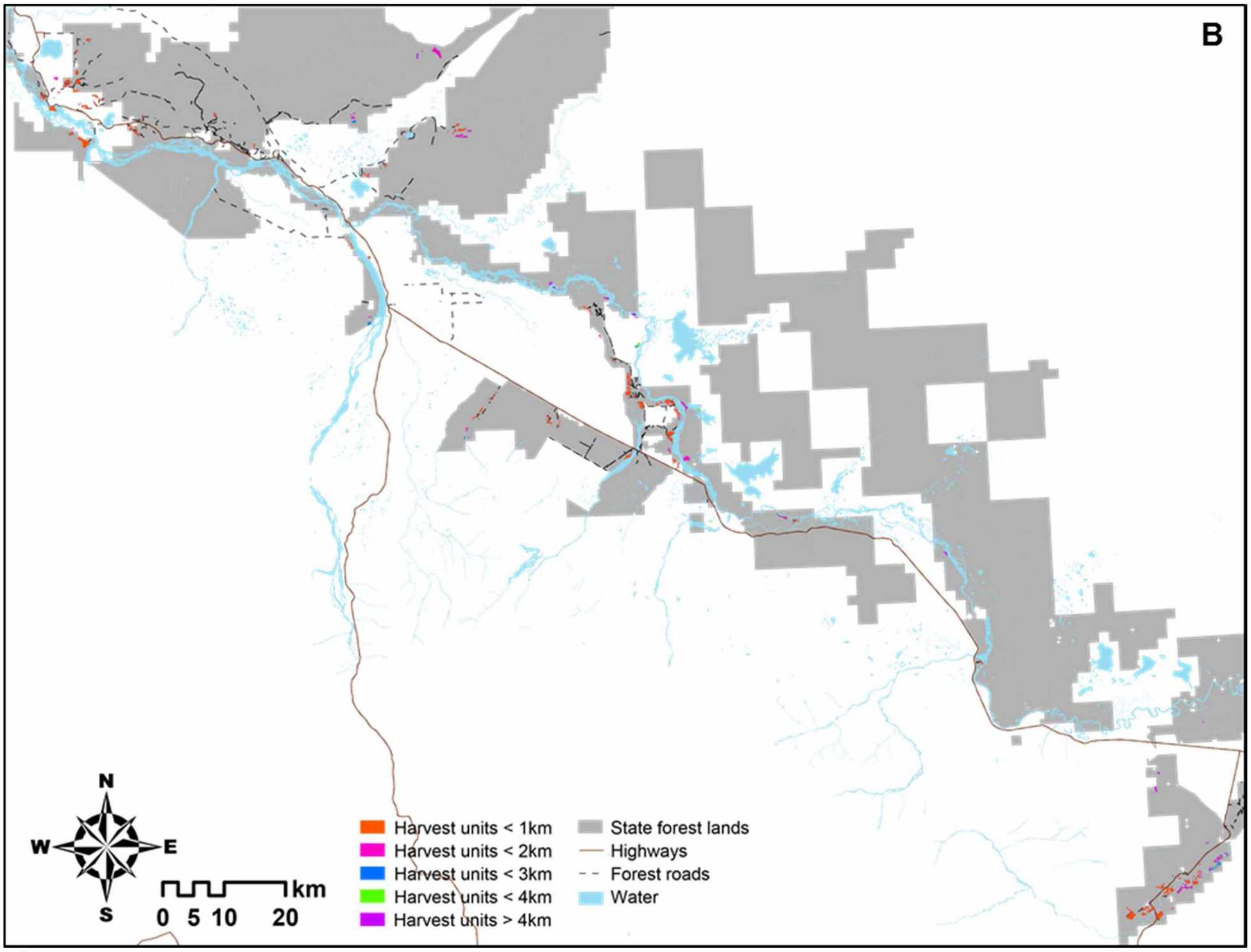


Figure 5.3 cont.

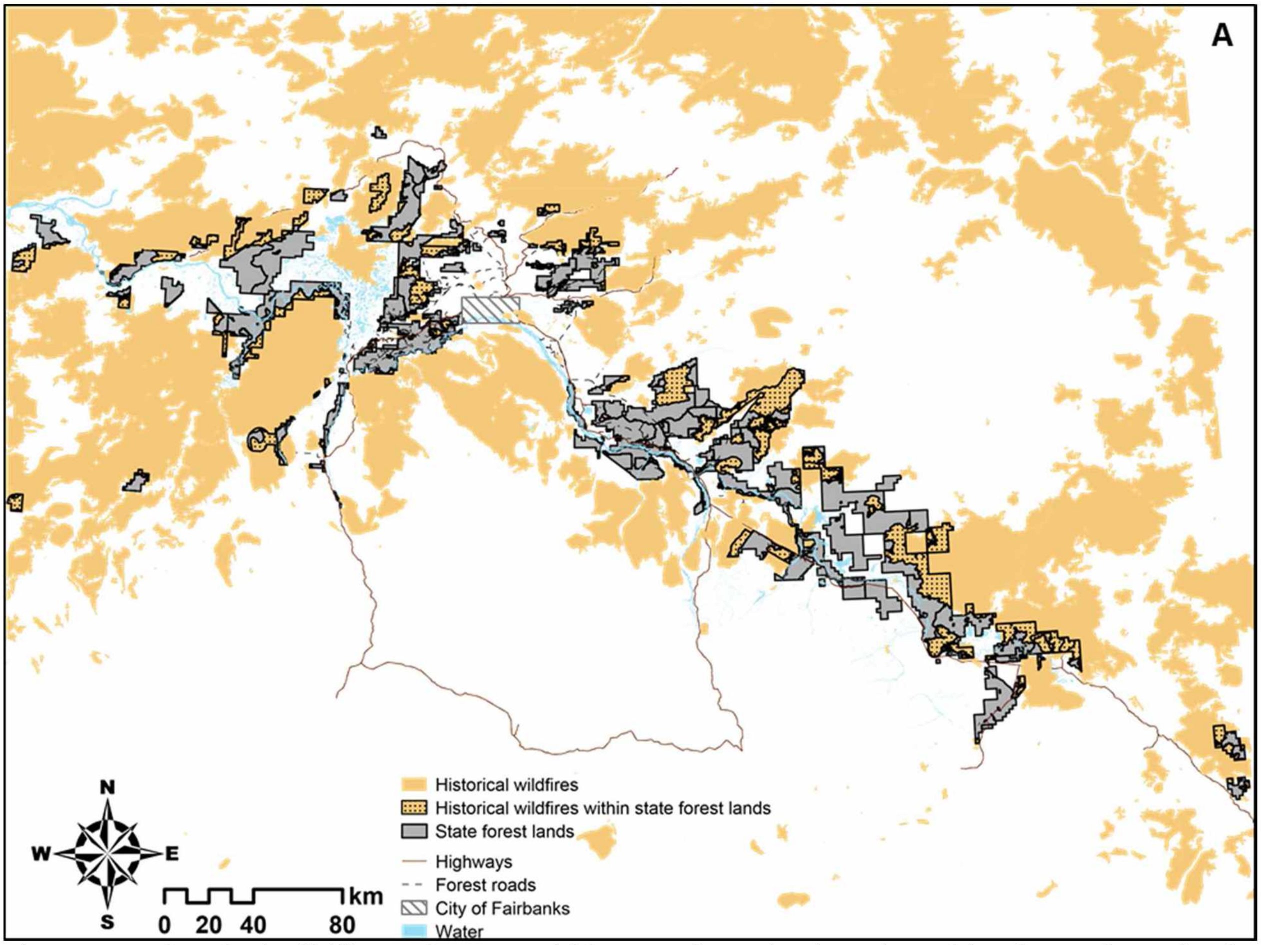


Figure 5.4 Historical wildfire perimeters within state forest lands and outside of state forest lands in the Tanana Valley. (a) The whole state forest lands and (b) the part of Fairbanks and Kantishna Management areas.

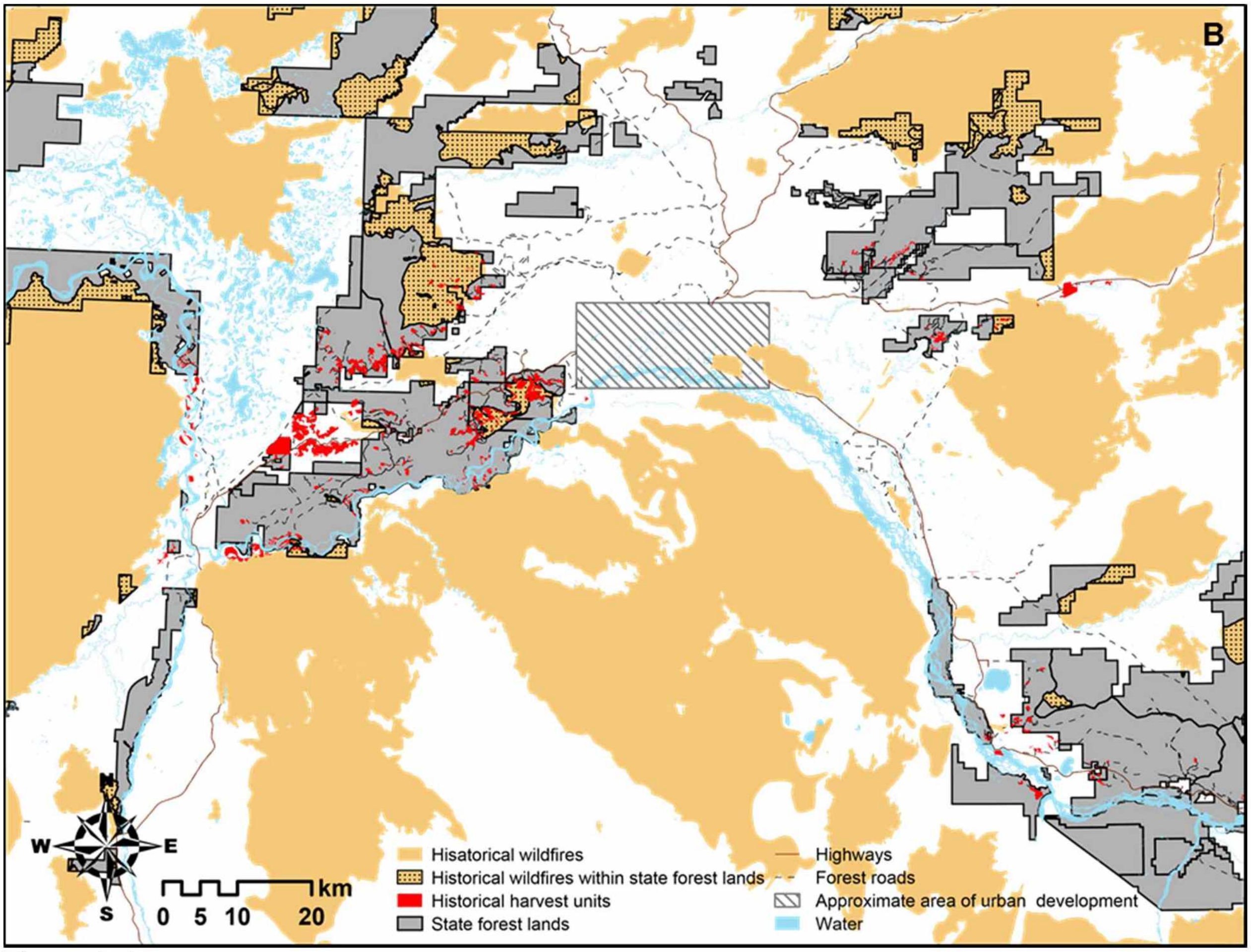


Figure 5.4 cont.

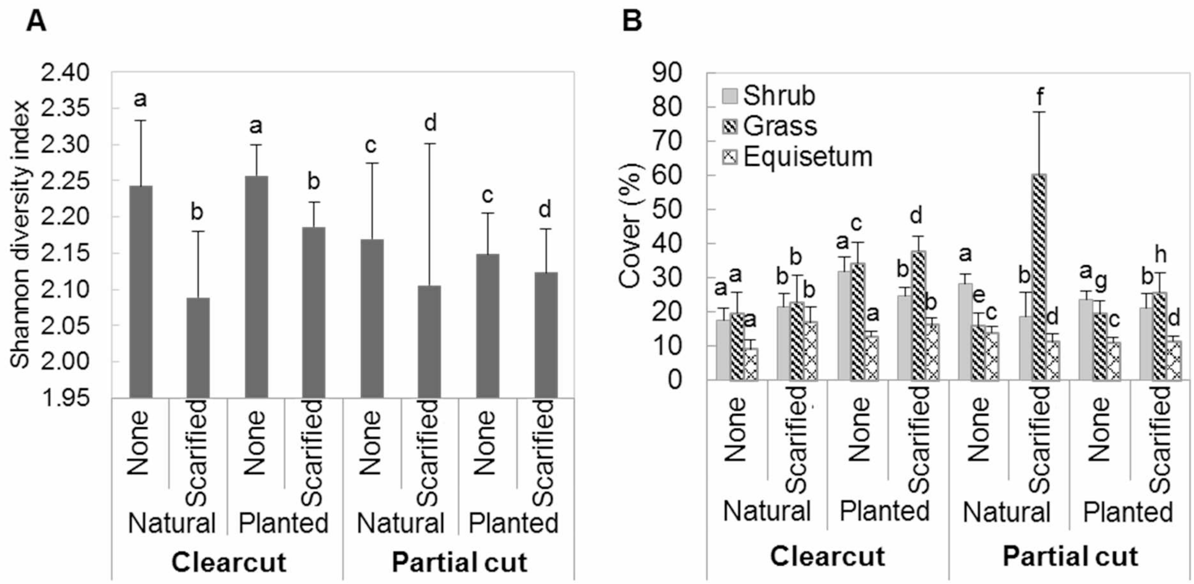


Figure 5.5 Comparisons in (a) Shannon diversity index (*H*) and (b) understory vegetation cover (%) of shrub, grass, and Equisetum spp. between harvest type, site preparation method, and reforestation technique. Analysis of covariance was used to identify significance difference between harvest type, site preparation method, and reforestation technique for Shannon diversity index. Multivariate analysis of covariance was used to identify significance difference between harvest type, site preparation method, and reforestation technique for vegetation cover. The result of vegetation cover is only shown here for the life forms that had significant difference. Small letters above the bars represent statistical significance within each response variables. Error bars represent 95% confidence intervals.

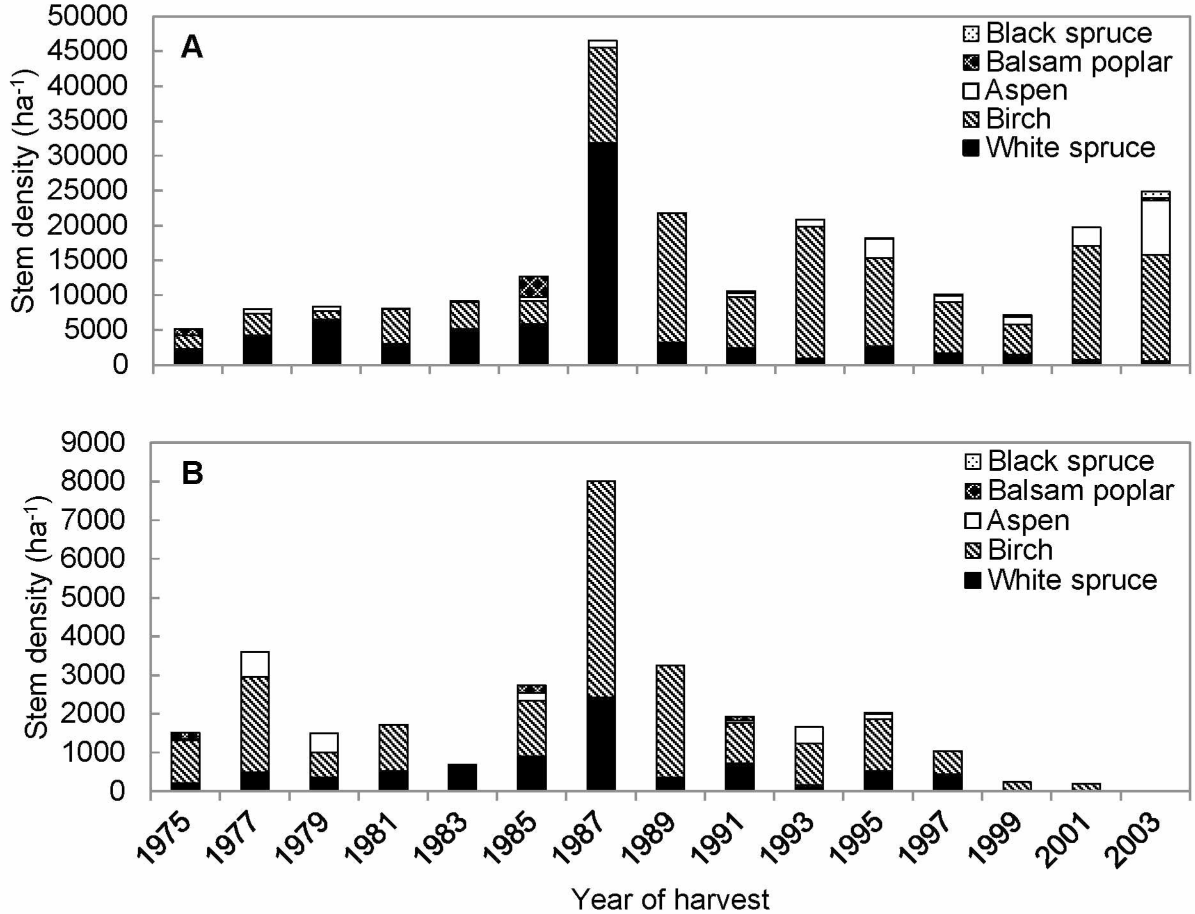


Figure 5.6 Stem density (ha^{-1}) by two year classes of date of harvest by species for (a) all diameters and (b) large stems (DBH $\geq$ 2.5 cm).

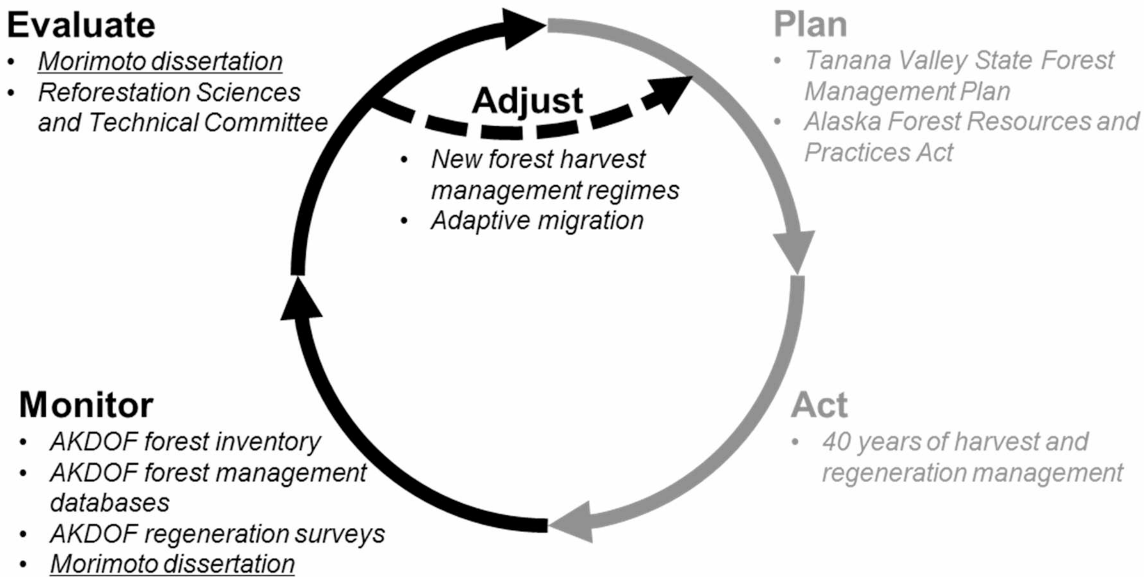


Figure 5.7 Conceptual framework of adaptive management in central Interior Alaska boreal forest adopted from (Stankey *et al.*, 2005).

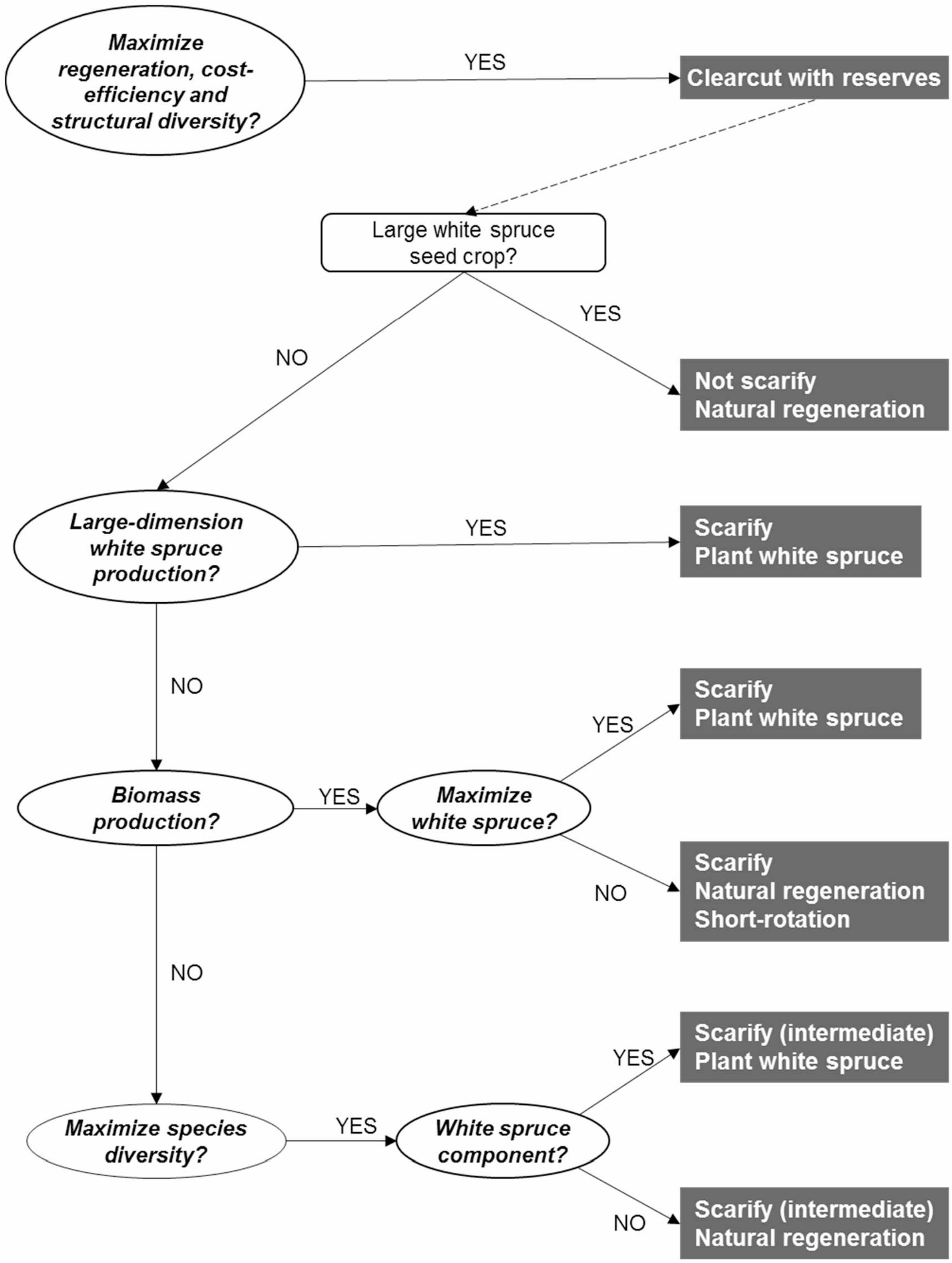


Figure 5.8 Management implication under a steady-state boreal forest environment. Applies only to white spruce harvest and only considers outcomes within-stand, not between stands (spatial component).

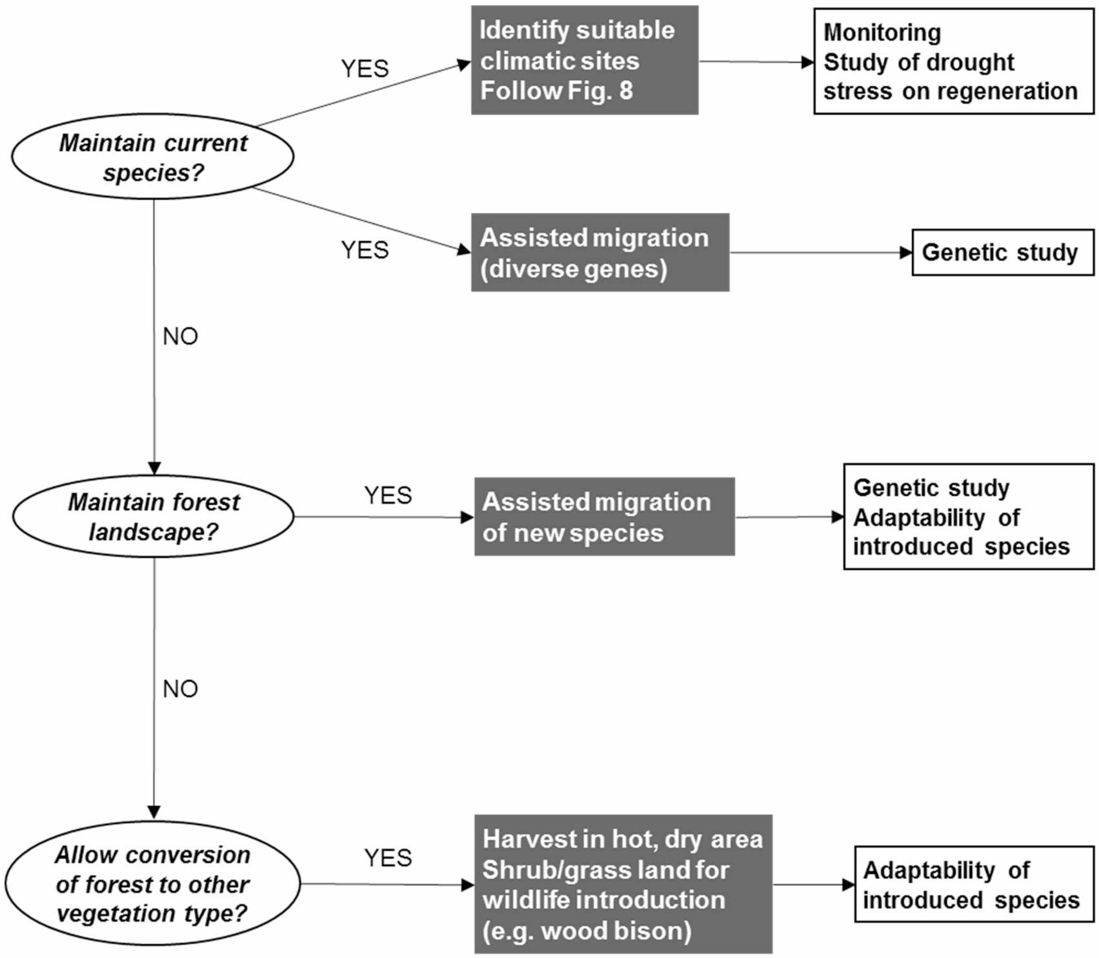
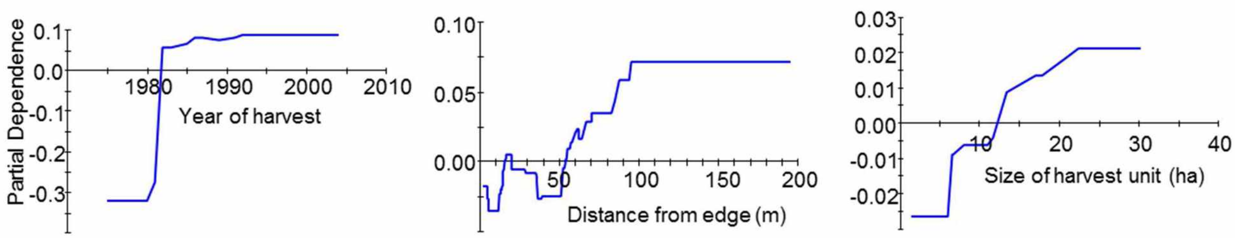


Figure 5.9. Adaptive management implications under a warming climate.

5.13. Appendix

Appendix 5.1. Methods and results of moose browse data. The analysis was conducted using a TreeNet algorithm, which falls within the group of stochastic gradient boosting, machine learning algorithm. TreeNet creates many weak learners with improvements using the residuals from the previous trees creating a strong learner that is optimized (Friedman *et al.*, 2000). Stochastic gradient boosting in general improves upon gradient boosting by drawing random subsets at each iteration (Hastie *et al.*, 2009). Partial dependence plots show the dependence of the response on the predictor variable when all other variables are held at their mean (Hastie *et al.*, 2009). Partial dependence plots useful in identifying the effects of Y-axes display the partial dependence value of prediction being 1 (present/high). Below are partial dependence plots for predictors with high importance for moose browse occurrence.



Appendix A

Permission from a coauthor to include chapters in the dissertation

Miho,
You have my permission to use Chapter 2 and 3 in your Dissertation as they represent original work that contributes knowledge to the subject and were the result of your work in planning, conducting, analysis, and reporting during these last 5 years.

All the best,
Brian Young

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Your letter/email permission for the thesis

Brian Young <BrianYoung@landmark.edu> Fri, Jun 24, 2016 at 5:20 AM
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Miho,

You have my permission to use Chapter 2 and 3 in your Dissertation as they represent original work that contributes knowledge to the subject and were the result of your work in planning, conducting, analysis, and reporting during these last 5 years.

All the best,

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Appendix B

Data on post-harvest regeneration in central Interior Alaska

Abstract

This dataset contains the record of post-harvest regeneration in Fairbanks and Kantishna areas of Tanana Valley State Forest and forest classified land. This data include harvest unit, plot, species, size class, density, status, origin, diameter, and height of white spruce, birch, aspen, balsam poplar, black spruce, alder spp., and willow spp.

Data

Dataset include all tree measured in 670 plots from 30 harvest units. The original tree measurement dataset and related metadata will be made available at Bonanza Creek LTER website (http://www.lter.uaf.edu/).

Experimental design and data collection

Experimental design

We investigated 30 separate harvest units located in the Fairbanks and Kantishna areas of state forest lands from the Fairbanks office of the Alaska Department of Natural Resources Division of Forestry (AKDOF) Forest Management Database (Alaska Division of Forestry, 2013). The FMD is a GIS-based database which includes the location and types of all forest management activities that has occurred on state lands within the Fairbanks and Kantishna areas (see Figure B.1) since 1972. For more detail and request of the FMD, contact Alaska Department of Natural Resources, Division of Forestry Fairbanks office. We selected representative harvest units that were evenly distributed across harvest types (16 clearcut and 14 partial cut units), site preparation methods (11 scarified and 19 unscarified units), reforestation techniques (16 planted and 14 naturally regenerated units), year of timber sale, and size of harvest units (Table B.1). Sample harvest units were also selected to achieve wide geographical coverage across the study region.

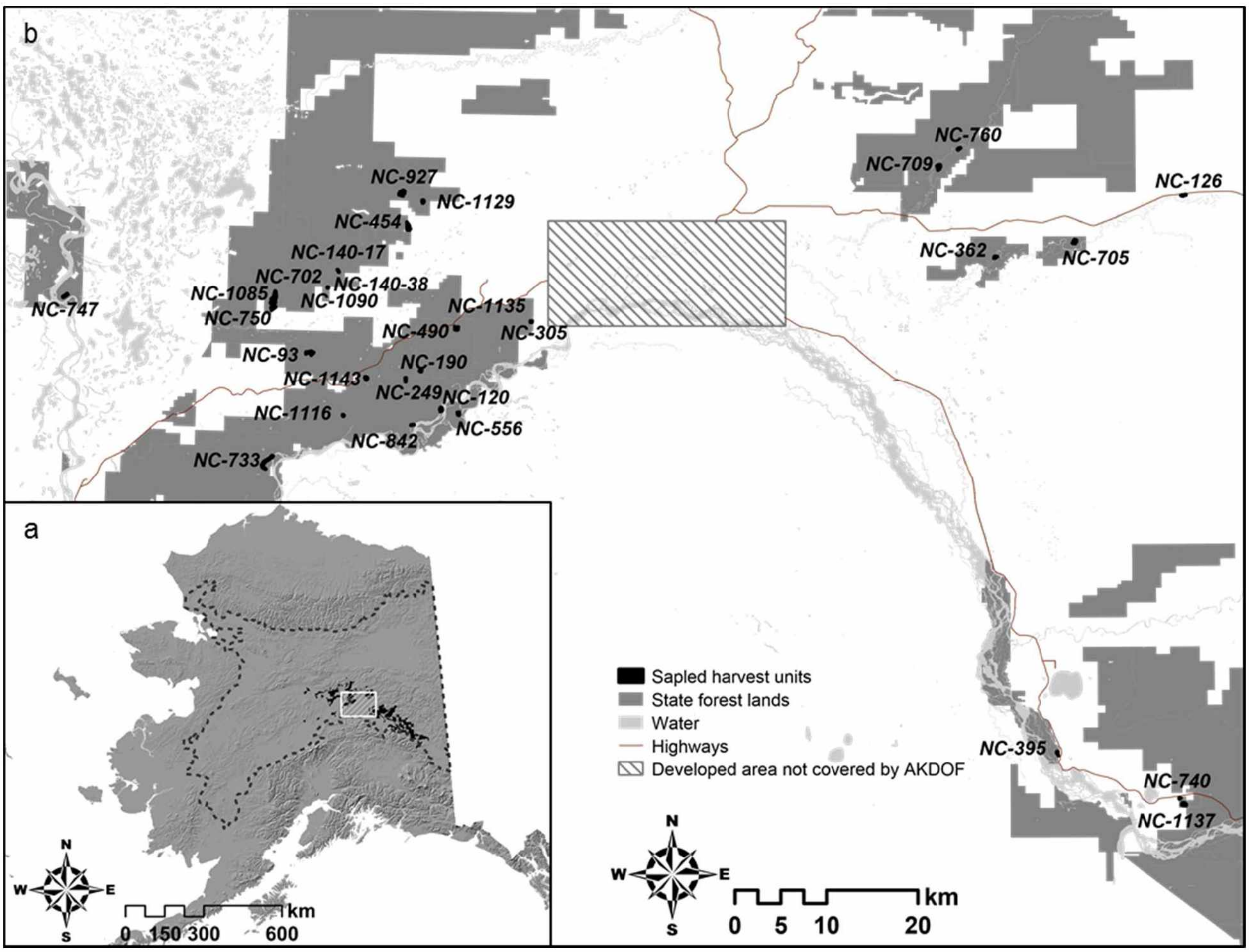

Figure B.1. Map of study area. (a) Study area (white box) is on state forest lands (black polygon) within Interior Alaska boreal region (dashed line; Nowacki *et al.*, 2001). (b) Sampled harvest units are distributed within Kantishna and Fairbanks areas of Tanana Valley State Forest and forest classified lands. NC- followed by number are sampled harvest units number.

Table B.1. Sampled harvest units

Unit	Size (ha)	# plots (calculated)	# plots (sampled)	Logged year	Harvest type	Site preparation	Reforestation
NC-120	10.4	41	41	1975	Partial cut	None	Plant
NC-93	17.9	76	35	1975	Partial cut	None	Natural
NC-190	5.1	22	22	1977	Clearcut	Scarify	Natural
NC-126	5.7	22	22	1978	Partial cut	None	Natural
NC-140-17	2.5	8	8	1979	Clearcut	None	Natural
NC-249	5.0	22	22	1980	Clearcut	Scarify	Natural
NC-362	4.4	15	15	1981	Partial cut	None	Natural
NC-140-38	1.5	7	7	1982	Clearcut	Scarify	Natural
NC-395	5.1	21	21	1983	Clearcut	None	Natural
NC-490	8.4	32	32	1985	Clearcut	None	Natural
NC-556	6.6	26	26	1986	Clearcut	None	Plant
NC-305	3.5	11	11	1987	Partial cut	Scarify	Plant
NC-705	11.0	44	44	1989	Clearcut	Scarify	Plant
NC-454	20.4	87	44	1991	Clearcut	Scarify	Plant
NC-740	1.9	8	8	1991	Clearcut	None	Plant
NC-709	17.2	71	35	1991	Clearcut	Scarify	Plant
NC-842	2.1	7	7	1992	Partial cut	None	Natural
NC-733	30.3	120	44	1992	Clearcut	Scarify	Plant
NC-702	2.0	9	9	1993	Clearcut	None	Plant
NC-747	8.0	31	31	1994	Clearcut	None	Plant
NC-750	9.8	41	41	1995	Clearcut	Scarify	Plant
NC-1085	22.6	94	47	1996	Partial cut	Scarify	Plant
NC-1137	13.5	55	29	1997	Clearcut	None	Plant
NC-927	22.5	90	43	1998	Partial cut	None	Plant
NC-760	3.4	13	13	1998	Partial cut	None	Natural
NC-1129	6.0	22	22	1999	Partial cut	None	Plant
NC-1090	1.4	7	7	1999	Partial cut	None	Natural
NC-1135	11.7	49	49	2002	Partial cut	None	Plant
NC-1116	2.4	9	9	2003	Partial cut	Scarify	Natural
NC-1143	6.7	28	28	2004	Partial cut	None	Natural

We used 1.69 m radius circular plots which is the same plot size as AKDOF regeneration survey (Alaska Division of Forestry, 2008). We determined sampling intensity based on a preliminary test of sampling efficiency using a censused population of white spruce located in the study region. Based on this analysis, we used four plots ha^{-1} as our sampling intensity. To determine the placement of plots, we created a virtual 50 m × 50 m grid with points at the center of each cell over the entire study area using ArcGIS (ESRI, 2013; Figure B.2). The points falling within the selected harvest units represented the center of the plots. We prioritized sampling a large number of harvest units over intensive sampling in a single harvest unit to cover greater area, and more replications of management practices and years. Because of this strategy, when the calculated number of plots was greater than 50, the sampling intensity was truncated into 50 or fewer by sampling every other or every third plot. In units where only every other plot was sampled, plots were evenly distributed starting from the first plot (Figure B.2).

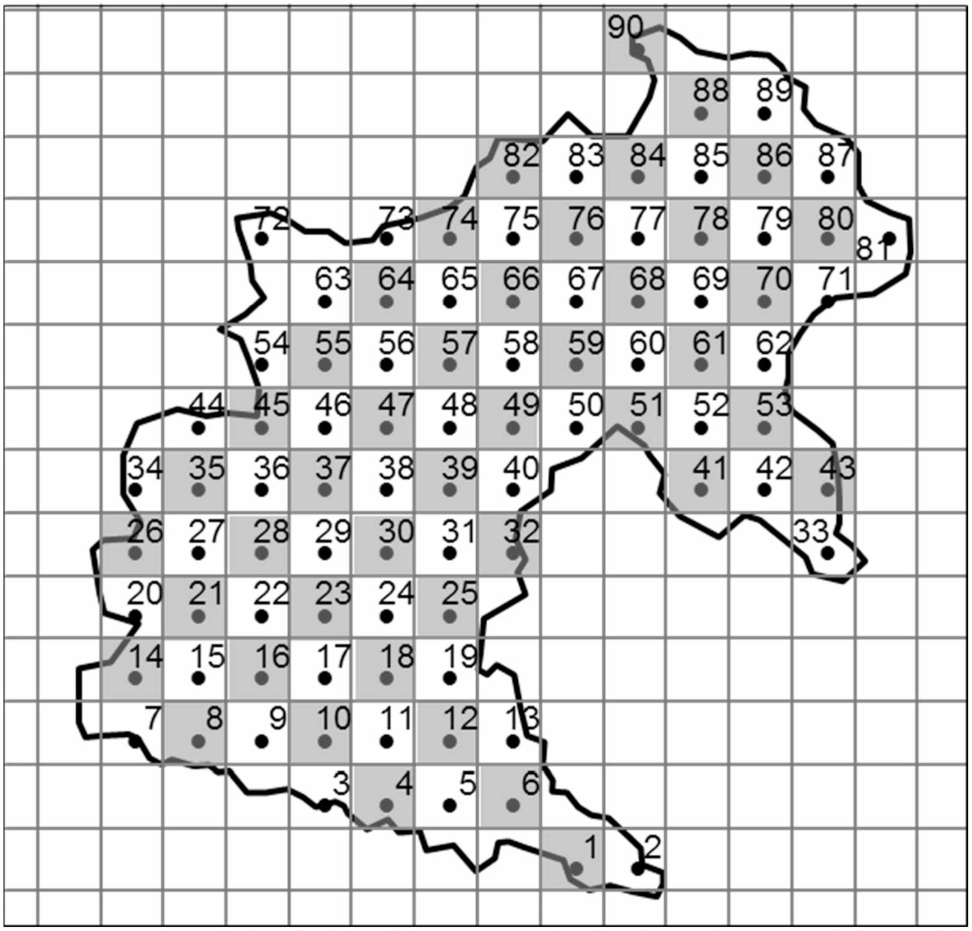

Figure B.2. Example of plot placement and selection. The size of the grid is 50 m. Dots represent plots and the numbers above them represent plot labels. In units with more than 50 plots, every other plot was selected (shaded cells).

Field sampling

Field sampling was conducted during the summers of 2013 and 2014. Within each plot, we recorded species, size class, number of stems for smaller stems than threshold and dead stems, origin, diameter at breast height (DBH)/basal diameter, total height, age (white spruce), crown class, and location, degree, and agent of damage. In odd number plot, we measured all the variables. By contrast, in even number plots, we only measured species, size class, number of stems for smaller stems than threshold, origin, diameter at breast height (DBH)/basal diameter, and total height to increase the number of plots and units measured.

Species measured include white spruce (ws; *Picea glauca* (Moench) Voss), birch (br; *Betula neoalaskana* Sarg.), aspen (as; *Populus tremuloides* Michx.), black spruce (bs; *Picea mariana* (Mill.)), balsam poplar (bp; *Populus balsamifera*), larch (tr; *Larix laricina*), alder spp. (al; *Alnus* spp.), and willow spp. (wl; *Salix* spp.). We used three size classes: 1) < 1 m height, 2) ≥ 1 m height but < 1 cm DBH, and 3) ≥ 1 cm DBH. Status includes 1) live and 2) dead. Origin are 0) residual, 1) sucker, 2) natural, 3) planted. Planted white spruce seedlings were distinguished from seedlings of natural origin based on age, growth pattern in early age, and alignment in planted rows with other white spruce stems when visible. Residual stems were distinguished from regeneration based on estimated age of the tree.

Except for live white spruce, we counted number of stems, if the stem falls within size classes 1 or 2, by species, size class, status, and origin (Figure B.3). For live white spruce, we counted number of stems when the stem is smaller than 30 cm in height (Figure B.3). When a live white spruce was 30 cm or taller, we measured total height and basal diameter, unless the tree was ≥ 1.37 m in height in which case we measured height and DBH (Figure B.3). For live birch, aspen, balsam poplar, black spruce, alder, and willow size class 3 stems, we measured

DBH and height (Figure B.3). We verified that a strong proportional relationship exists between height of stems and DBH for alders (unpublished data). To reduce time spent on alder, we measured the height of the tallest stem (ramet) emerging from same root crown, and only DBH for the remaining ramets.

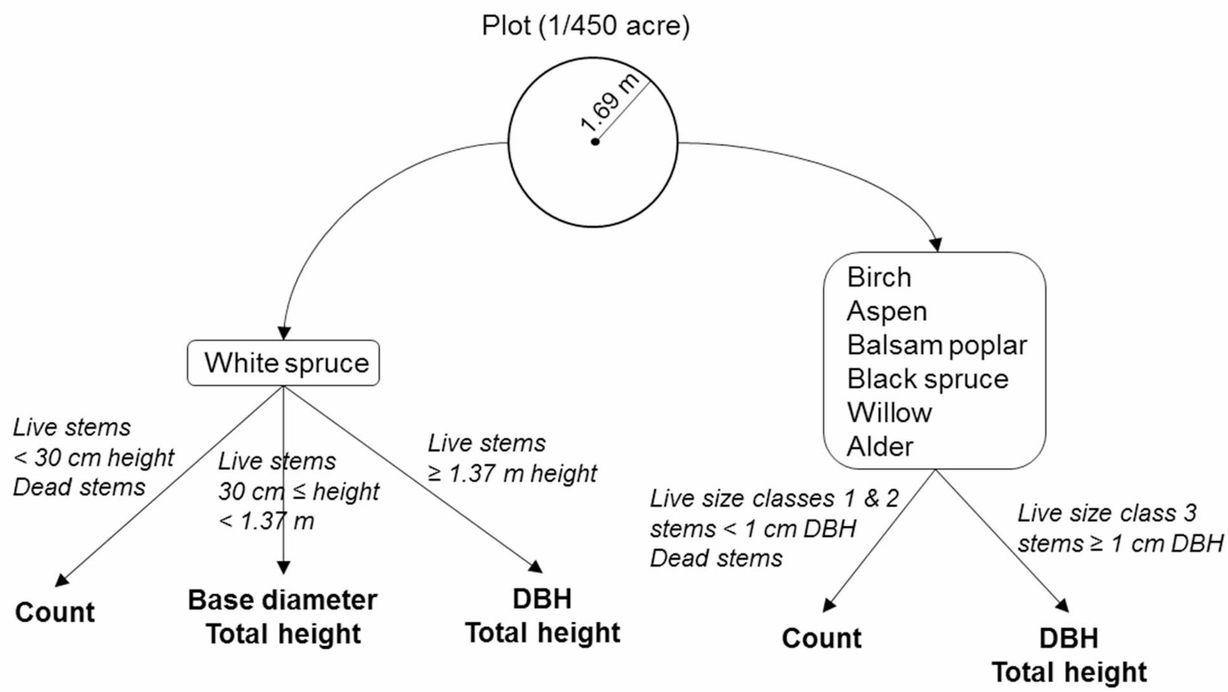

Figure B.3. Diagram of sampling procedure.

We counted whirl to measure age of white spruce. We recorded crown class, and location, degree, and agent of damage for each live stem which were measured for diameter and height or group of live stems which were counted. In the case for the group of live stems, crown class was determined by dominating crown class within the group and all the existing damage within the group was recorded.

Crown class includes: 1) open; 2) dominant; 3) co-dominant; 4) intermediate; 5) overtopped. Damage location is category including na = none; st = stem; br = branch; ld = leader; cr = crown; nw = new foliage; of = old foliage; bd = bud; vg = vegetative competition; ls = layered seedling. Damage degree is category including: 1 = 0-25%; 2 = 25-50%; 3 = 51-100%;

4 = dying; 5 = dead. Damage agent is category including 10 = leaf chewers; 11 = leaf miners; 12 = leaf rollers; 13 = sapsuckers (aphids); 14 = budworm; 15 = other insect; 18 = nutrient deficiency; 20 = moose; 21 = hare; 25 = squirel; 26 = small animals; 27 = snow/ice; 28 = wind; 31 = drought; 33 = natural; 35 = shrubs; 36 = trees; 37 = logging damage; 39 = crush/rubbing; 40 = botr; 41 = other.

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